DMIC Report 164
December 6, 1961

SEMIAUSTENITIC PRECIPITATION-HARDENABLE STAINLESS STEELS

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1. To collect, store, and disseminate technical information on the current status of research and development of the above materials.

2. To supplement established Service activities in providing technical advisory services to producers, melters, and fabricators of the above materials, and to designers and fabricators of military equipment containing these materials.

3. To assist the Government agencies and their contractors in developing technical data required for preparation of specifications for the above materials.

4. On assignment, to conduct surveys, or laboratory research investigations, mainly of a short-range nature, as required, to ascertain causes of troubles encountered by fabricators, or to fill minor gaps in established research programs.

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DMIC Report 164
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SEMIAUSTENITIC PRECIPITATION-HARNENABLE STAINLESS STEELS

by

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to

OFFICE OF THE DIRECTOR OF DEFENSE RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
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PREFACE

In 1956 the Titanium Metallurgical Laboratory (predecessor to Defense Metals Information Center) issued TML Report No. 48, "The Engineering Properties of Precipitation-Hardenable Stainless Steels". This report described the engineering characteristics of Stainless W, 17-7 PH, 17-4 PH, and AM 350. Included was an appendix of producers' data. Because in certain respects these materials were competitive with titanium for aircraft applications, TML prepared Report No. 48 to place in perspective the position of titanium in the metals industry.

By 1959 TML Report No. 48 was out of date. Two new precipitation-hardenable stainless steels, AM 355 and PH 15-7 Mo, were on the market. In addition, new treatments had been developed. More was known about mechanical properties. The semiaustenitic grades in particular were becoming very popular; they were termed the "workhorse of the aircraft industry". Meanwhile the Defense Metals Information Center had been organized. Whereas the scope of TML was largely confined to titanium, DMIC has responsibility for a broad range of metals used in defense applications. Under these circumstances, DMIC prepared two new reports: 111 - "The Physical Metallurgy of Precipitation-Hardenable Stainless Steels"; and 112 - "Physical and Mechanical Properties of Nine Commercial Precipitation-Hardenable Stainless Steels". These reports covered martensitic, semiaustenitic, and austenitic precipitation-hardenable stainless steels.

By mid-1961 progress had once again outdated many portions of Reports 111 and 112. The producers of the semiaustenitic materials had introduced several new alloys. In addition, new thermal and mechanical treatments had been developed to improve the properties of the original steels.

On the other side of the coin, the situation regarding the martensitic precipitation-hardenable stainless steels and the austenitic precipitation-hardenable stainless steels has, for the most part, remained static. The information on these materials in Reports 111 and 112 is still accurate and nearly up to date.

In view of these developments, this report has been prepared. It covers both the physical metallurgy and the properties of the semiaustenitic precipitation-hardenable stainless steels. Property data have been placed in appendices at the back of the report. Only illustrative property values are given in the text. The emphasis in this report is on the new aspects of semiaustenitic materials. Older information, however, is also included for the sake of completeness.

The cooperation of Allegheny Ludlum Steel Corporation and Armco Steel Corporation in providing much of the information in this report is gratefully acknowledged.

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SUMMARY

The first member of the family of semiaustenitic precipitation-hardenable stainless steels, 17-7 PH, was born during World War II. In the mid-fifties it was joined by three siblings: AM 350, AM 355, and PH 15-7 Mo. These steels have since grown to maturity. Late arrivals to the family include AM 357 and noncommercial AM 359.

The semiaustenitic precipitation-hardenable stainless steels remain austenitic on cooling from a solution heat treatment at about 1950 F. In this form they are readily fabricable. Subsequent treatment at about 1400 F or at about 1725 F depletes the austenite of chromium and carbon to the extent that martensite forms on cooling to room temperature or -100 F, respectively. Final hardening is effected by tempering, or aging, at 750 to 1100 F.

The semiaustenitic precipitation-hardenable stainless steels may be obtained as transformed at the mill by cold rolling. In this condition they lack the good formability of solution-heat-treated material. However, the fabricator need only temper them to obtain very high strengths.

These steels have a combination of good formability, high strength, and excellent corrosion resistance that is not easily matched by other materials.

INTRODUCTION

Stainless steels were developed and patented in the United States, Canada, Great Britain, Germany, and France during the second decade of this century. By the late thirties three classes of stainless steels — the martensitic, ferritic, and austenitic classes — had become commercially important. Semiaustenitic precipitation-hardenable stainless steels were developed during World War II when the need for stronger corrosion-resistant materials was accentuated.

Wartime research by G. N. Goller at Armco Steel Corporation, Baltimore, Maryland, led to the development of 17-7 PH. This steel, described in United States Patents 2,505,763 and 2,505,764, was introduced in 1948. 17-7 PH was unique in that it was soft, austenitic, and formable as solution annealed, but could be hardened to a high strength level by thermal treatments alone. It had an excellent combination of formability, strength, and corrosion resistance.

Work in the early fifties by Dr. Aldoph J. Lena at Allegheny-Ludlum Steel Corporation, Brackenridge, Pennsylvania, led to the development of AM 350 and AM 355. AM 350 was introduced in 1954, AM 355 in 1955. Both steels are described in United States Patent 2,799,602. Like 17-7 PH, AM 350 and AM 355 were austenitic as solution annealed, but could be hardened by thermal treatment alone.

The treatment specified by Goller to harden 17-7 PH was termed "double heat treatment". It consisted of a conditioning treatment at 1400 F followed by an age at 1050 F. During the conditioning treatment the precipitation of chromium carbides reduced the stability of the austenite so that it would transform on cooling to room temperature. During aging, the coherent precipitation of an intermetallic compound further hardened the structure.

Dr. Lena specified a similar treatment for AM 350 and AM 355. In addition he developed another hardening sequence termed subzero cooling and tempering. When his steels were conditioned at about 1750 F they remained largely austenitic on cooling to room temperature, but they could be transformed by cooling to -100 F. Subsequent tempering at 850 F resulted in additional strengthening, by a mechanism then unknown.

By 1956 when Armco introduced PH 15-7 Mo, a molybdenum-containing modification of 17-7 PH, both hardening sequences were practiced on all four steels. The sequence involving subzero cooling, because it results in higher strength, has become the more popular in recent years.

The demand for very-high-strength stainless steels, for applications such as rocket-motor cases, has been growing. Accordingly, hardening sequences were developed involving combined thermal and mechanical treatments and capable of developing very high strengths. These hardening sequences most often rely on severe cold work to transform the material.

Recently J. E. Mosser at Allegheny-Ludlum developed two high-carbon semiaustenitic precipitation-hardenable stainless steels. AM 357, a steel developed especially for very high-strength applications, became available in 1959. AM 359, an aluminum-containing sheet and bar product, is not available commercially. The properties of this steel, nevertheless, are included to show the combination of strength and ductility that can be obtained in alloys of this type.

The final step in the handling of semiaustenitic precipitation-hardenable stainless steels is usually a treatment at a temperature in the range 750 to 1100 F. In the case of AM 350, AM 355, and AM 357, this treatment is termed "tempering". In the case of the aluminum-containing steels, AM 359, 17-7 PH, and PH 15-7 Mo, it is termed "aging". The martensitic structure in all six steels is certainly tempered during this final treatment. Since 17-7 PH was introduced, however, it was thought that aluminum-containing martensitic steels are strengthened by coherent precipitation of a hardening compound during the final treatment. Therefore these steels were "aged". On the other hand, when AM 350 was introduced, it was thought that the martensite reaction alone accounted for the major portion of the hardening. Thus AM 350 was "tempered". Recent evidence strongly indicates that all six steels are truly precipitation hardenable. The early terminology, however, has been retained.

Some confusion exists about the naming of precipitation-hardenable stainless steels. The steels discussed in this report are all semiaustenitic precipitation-hardenable stainless steels. "Semiaustenitic" refers to the ability of these steels to remain soft and austenitic after a solution anneal and to their ability to be martensitized subsequently by conditioning and cooling. "Precipitation hardenable" refers to the ability of these steels to be strengthened by the coherent precipitation of a hardening compound during aging. Semiaustenitic stainless steels need not be precipitation hardenable, but all are thought to be. Likewise, all precipitation-hardenable stainless steels are not semiaustenitic. Indeed, both martensitic precipitation-hardenable stainless steels (e.g., 17-4 PH, Stainless W) and austenitic precipitation-hardenable stainless steels (e.g., A-286, HNM) have been developed. One should avoid the use of "precipitation-hardenable stainless steels" or "PH steels" when referring specifically to the semiaustenitic variety. These phrases should be reserved for use in the generic sense. It is incorrect to refer to precipitation-hardenable stainless steels in general by the term "semiaustenitic".

It will become increasingly important to use a consistent nomenclature as new alloyed steels are developed. The advent of a series of iron-nickel high-strength alloys has demonstrated this. These new materials are precipitation-hardenable. They are steels. Some, but not all, are semiaustenitic; but this term is usually not applied. None is stainless.

One colloquialism sometimes results in misunderstanding. Both 17-7 PH and AISI 301 are nicknamed "17-7". Confusion can be avoided by always voicing "PH" when referring to 17-7 PH.

Work toward still better materials and treatments is continuing. The state of the art is not static.

The first portion of this report discusses the classification of stainless steels and places in perspective the semiaustenitic precipitation-hardenable stainless steels. The second portion of the report discusses, in order, the characteristics of AM 350, AM 355, AM 357, AM 359, 17-7 PH, and PH 15-7 Mo. The final portion of the report consists of appendices of typical physical- and mechanical-property data. Design properties are not specified in these appendices. They will be found in other DMIC reports.

CLASSIFICATION OF STAINLESS STEELS

The stainless steels are essentially alloys of iron, carbon, and chromium, but they may also contain significant amounts of other alloying elements. Carbon may be present in amounts up to 1.25 per cent. Chromium, which is present in amounts ranging from 11.5 to 32 per cent, accounts for the remarkable corrosion and oxidation resistance of this series. Nickel heads the list of other alloying elements found in stainless steels. A major function of this element is to promote the presence of austenite. Molybdenum is often added to improve resistance to attack by halide solutions, to increase elevated-temperature strength, or both. Titanium, or columbium plus tantalum, is added to some stainless steels to prevent the formation of chromium carbides during certain thermal treatments. Chromium carbides precipitated during welding, for example, can severely reduce resistance to intergranular attack. Aluminum, titanium, and copper are believed to produce precipitation-hardening characteristics.

There are about sixty different stainless steels. Most of these belong to one of three families. ferritic, martensitic, or austenitic stainless steels. Some, however, belong to a fourth, new family, viz., semiaustenitic stainless steels. The assignment of a particular stainless steel to one of these four families is made on the basis of its structure, both at room temperature and at elevated temperatures. Structure, in turn, is a function of both composition and heat treatment.

Each ingredient of a stainless steel plays a dual role in defining structure. Each element plays one role at elevated temperatures and another during cooling from an elevated-temperature treatment. Both of these roles are summarized by Figure 1. The part played by elements at elevated temperatures is depicted by the upper portion of Figure 1; their function in defining structure during cooling is shown below the broken line.

The upper portion of Figure 1 shows that the elements present in stainless steels may be divided into two groups: ferrite promoters and austenite promoters. Ferrite promoters are those elements that, when added to the steel, encourage the presence of the ferrite phase at normal annealing temperatures. Examples of this group are chromium, molybdenum, silicon, aluminum, titanium, and phosphorus. Austenite promoters are those elements that favor the formation of austenite at elevated temperatures. Examples of austenite promoters are iron, nickel, carbon, manganese, nitrogen, and copper. Whether a stainless steel will be austenitic or ferritic at an elevated temperature depends on the relative proportions of the elements present from these two groups, as well as on the details of the annealing treatment.

Temperature, as well as composition, is an important factor in defining structure. There are upper limits to the temperature at which either a wholly ferritic or a wholly austenitic structure can be maintained. Figure 2 is a highly idealized pictorial aid illustrating the combined effects of composition and temperature on the phases present at elevated temperatures.

The lower portion of Figure 1 illustrates the effect of composition on structure during cooling. Although ferritic structures always remain ferritic on cooling, austenitic structures may undergo a transformation during cooling. Stainless steels

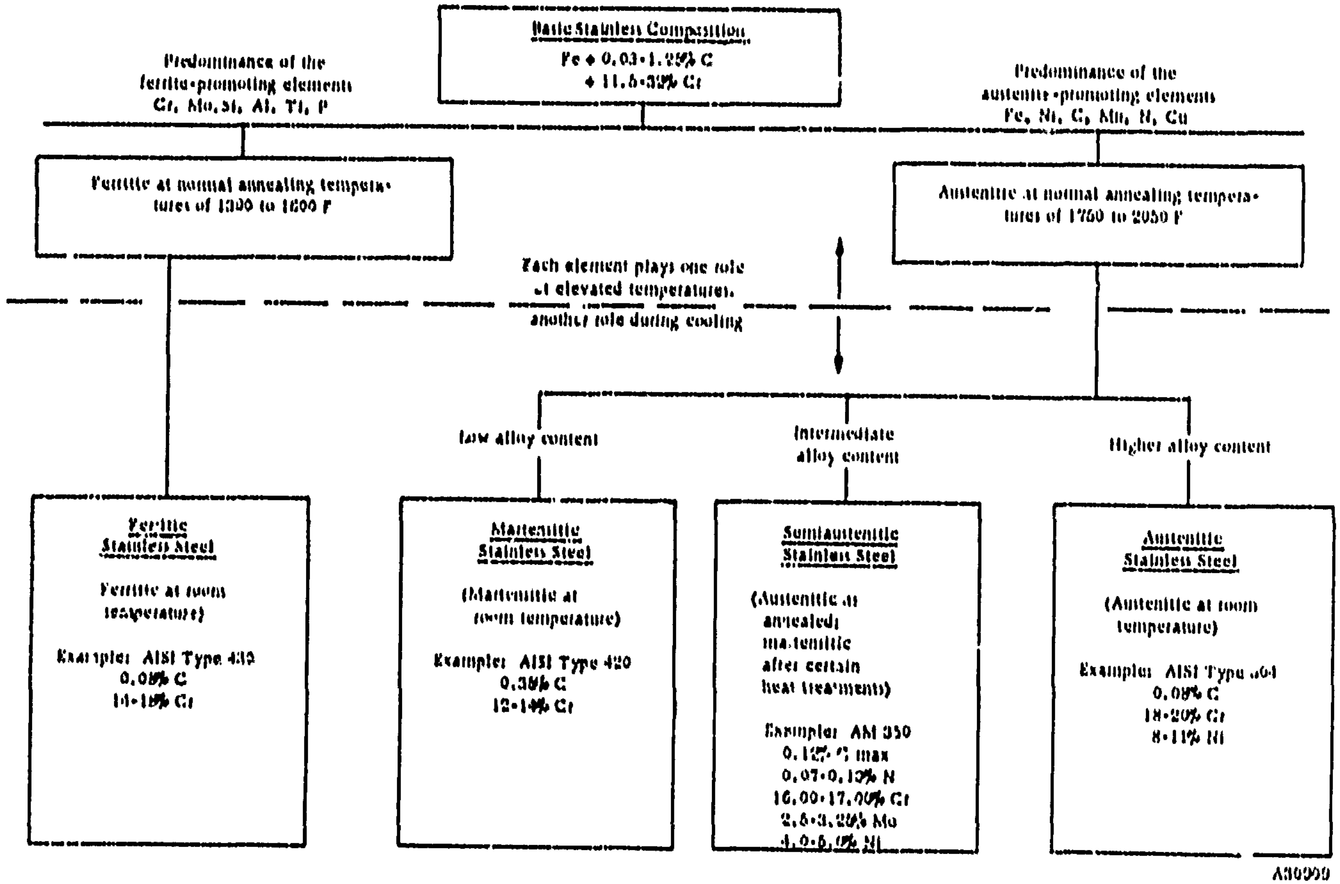


FIGURE 1. CLASSIFICATION OF STAINLESS STEELS BY COMPOSITION

that are austenitic at elevated temperatures but of low alloy content usually transform to martensite on cooling. Their highly alloyed counterparts usually remain austenitic. Those of intermediate alloy content may either transform or not, depending on how they are heat treated. Examples of the four families thus defined, the ferritic, martensitic, semiaustenitic, and austenitic families, are given in Figure 1.

Figure 3 illustrates how the alloy content of those stainless steels that are austenitic at elevated temperatures defines their structure at room temperature. Martensitic stainless steels often transform on cooling through the range 600 to 400 F. Austenitic stainless steels remain austenitic even on cooling to well below room temperature.

Semiaustenitic stainless steels when annealed at temperatures in the order of 2000 F (represented by Line A in Figure 3) remain austenitic on cooling to room temperature, or even well below. A subsequent treatment at a lower temperature (often termed a conditioning treatment or trigger anneal) allows chromium carbide particles to precipitate. This precipitation depletes the matrix of chromium and carbon; it has the effect of reducing alloy content. Semiaustenitic stainless steels conditioned at about 1700 F have an effective alloy content represented by Line B in Figure 3. They remain austenitic on cooling to room temperature, but can be transformed by cooling to -100 F. Those trigger annealed at about 1400 F are represented by Line C of Figure 3. They can be transformed by cooling to room temperature.

Metallurgists often use the symbol M_s to designate the temperature at which martensite begins to form from austenite on cooling. Thus, semiaustenitic stainless steels in the solution annealed condition have M_s temperatures well below room temperature. Depending on the trigger-anneal temperature, the M_s may be raised to room temperature or higher. The temperature at which transformation is complete on cooling is termed the M_f.

The advantage of semiaustenitic stainless steels is that they combine, in a single material, the excellent formability of the austenitic structure and the high strength of the martensitic structure. In addition they offer the remarkable corrosion resistance of the stainless series of alloys. This combination of qualities is unique among metallic materials.

There are two exceptions to the general rule that alloying elements lower the transformation range in stainless steels that are austenitic at elevated temperatures. Both aluminum and cobalt raise the transformation range. Cobalt, at least in significant quantities, is usually not found in stainless steels. Aluminum, however, is an important ingredient in 17-7 PH, PH 15-7 Mo, and AM 359. In these steels aluminum plays an important role in the balance of composition as well as being a precipitation hardener.

It may be helpful, in summary, to draw an analogy with a seesaw. Two boys on the ferrite side versus one boy on the austenite side represents a ferritic stainless steel. If two additional boys are now added to the austenite side, making three on the austenite side versus two on the ferrite side, a structure austenitic at elevated temperatures is represented. Provided that at least one more boy is on the austenite side than on the ferrite side a structure austenitic at elevated temperatures will always be maintained. But what happens on cooling is dependent on the total number of boys on

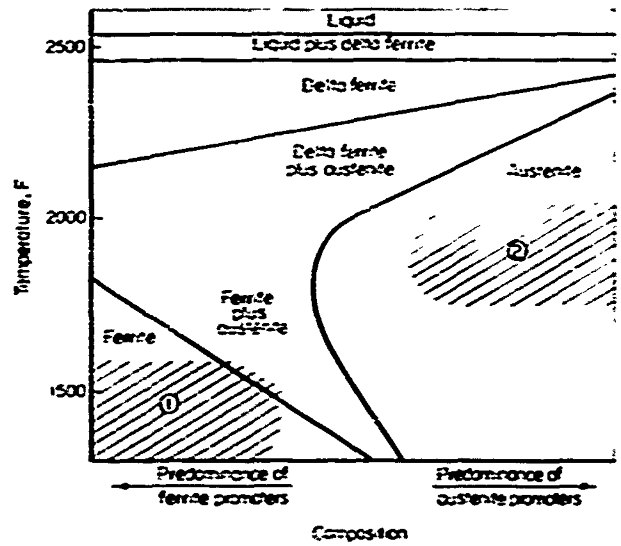


FIGURE 2. ELEVATED-TEMPERATURE CONSTITUTION OF STAINLESS STEEL

Cross-hatched areas represent those ranges of composition and temperature normally used to obtain (1) ferrite or (2) austenite.

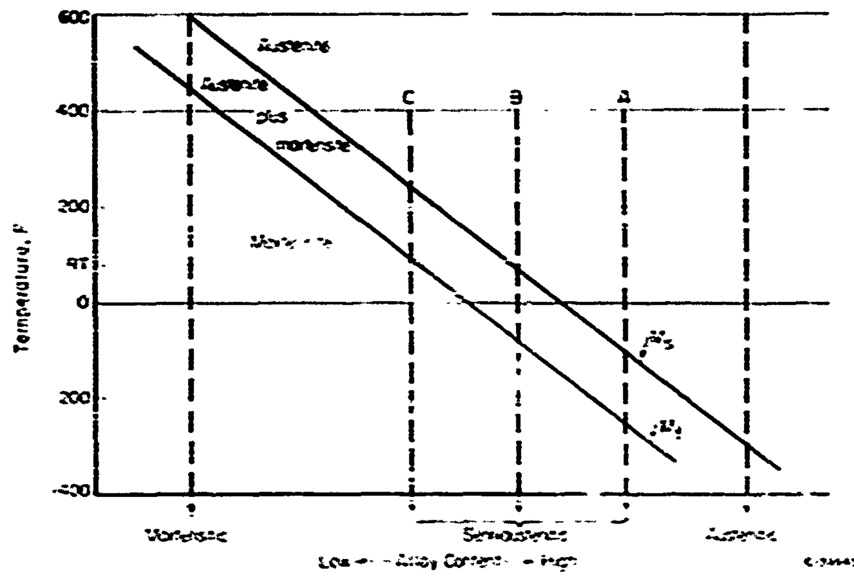


FIGURE 3. THE EFFECT OF ALLOY CONTENT ON TRANSFORMATION TEMPERATURES

the seesaw. Three boys on the austenite side versus two on the other might be the analog of intermediate alloy content, or a semiaustenitic stainless steel. Adding one boy to each side would then represent high alloy content, or an austenitic stainless steel. Or, removing one boy from each side would represent low alloy content, and a martensitic stainless steel. In this analogy aluminum might act as a helium-filled balloon tied to the austenite side of the seesaw.

AM 350

AM 350 is a semiaustenitic precipitation-hardenable stainless steel. It was developed and patented by Allegheny-Ludlum Steel Corporation. AM 350 is produced by Allegheny-Ludlum, by its subsidiary, Wallingford Steel Company, and under license by Universal-Cyclops Steel Corporation, Vanadium Alloys Steel Company, Carpenter Steel Company, and Crucible Steel Company. Although this steel is principally a sheet and strip product, it is also sold as foil, welded tubing, billets, bars, forgings, and wire. Typical uses include aircraft skin and structural components, ducts, tanks, springs, shafts, and nuclear reactor components.

AM 350 sheet and strip have the designation AMS 5548A; seamless tubing bears the designation AMS 5554; bars and forgings bear the designation AMS 5745.

Composition

AM 350 is a delicately balanced low-carbon, chromium-nickel stainless steel containing an addition of molybdenum to promote elevated-temperature strength. The complete composition is given below.

Element	Composition, per cent: Range	Nominal	Actual Example[a]
Carbon	0.08-0.12	0.10	0.09
Manganese	0.50-1.25	0.75	0.80
Phosphorus	0.04 max	--	0.020
Sulfur	0 03 max	--	0.015
Silicon	0.50 max	0.30	0.26
Chromium	16.00-17.00	16.50	16.46
Nickel	4.0-5.0	4.25	4.38
Molybdenum	2.5-3.25	2.75	2.71
Nitrogen	0.07-0.13	0.09	0.095
Iron	Balance	Balance	Balance

(a) Heat No. [illegible]

Availability

Allegheny-Ludlum makes a distinction between commercial materials and developmental materials. Commercial materials are those that have highly consistent properties after standard mill processing. Developmental materials are those for which insufficient processing or property data have been accumulated to allow firm guarantees of mechanical properties or delivery, or those which require special handling to obtain optimum or highly consistent properties. Commercial materials are available on standard mill orders; developmental materials are often available on special order. A partial listing of commercial materials is given below.

Form	Condition	Dimensions, inches Thickness	Width	Length
Sheet	H-annealed	0.010 - 0.125	24	10,000-lb coils
		0.016 - 0.156	36	10,000-lb coils
		0.025 - 0.062	36 - 48	120 in. max
		0.063 - 0.187	36 - 60	144 in. max
	CRT	0.010 - 0.125	24 - 36	--
Strip	H-annealed	0.010 - 0.187	1 - 23-15/16	--
	CRT	0.010 - 0.124	1 - 23-15/16	--
Foil	H-annealed or CRT	0.001 - 0.009	1 - 24	--

Treatment

AM 350 is solution heat treated, or H-annealed, at 1950 F before it leaves the mill. This treatment dissolves all carbides, recrystallizes the matrix, and makes it austenitic with 5 to 20 per cent delta ferrite. On cooling to room temperature this structure is retained. AM 350 as H-annealed is soft and formable. The M_s is well below room temperature.

After severe deformation AM 350 may be softened, by the fabricator, by H-annealing. In this operation it is important to observe the limits 1950 F ± 25 F. Lower temperatures tend to reduce formability; higher temperatures result in reduced strength and a higher delta ferrite content.

After the H-anneal, AM 350 may be treated by one of three sequences: double aging (DA); subzero cooling and tempering (SCT); or cold rolling and tempering (CRT). These treatments, with resulting typical properties, are outlined in Figure 4.

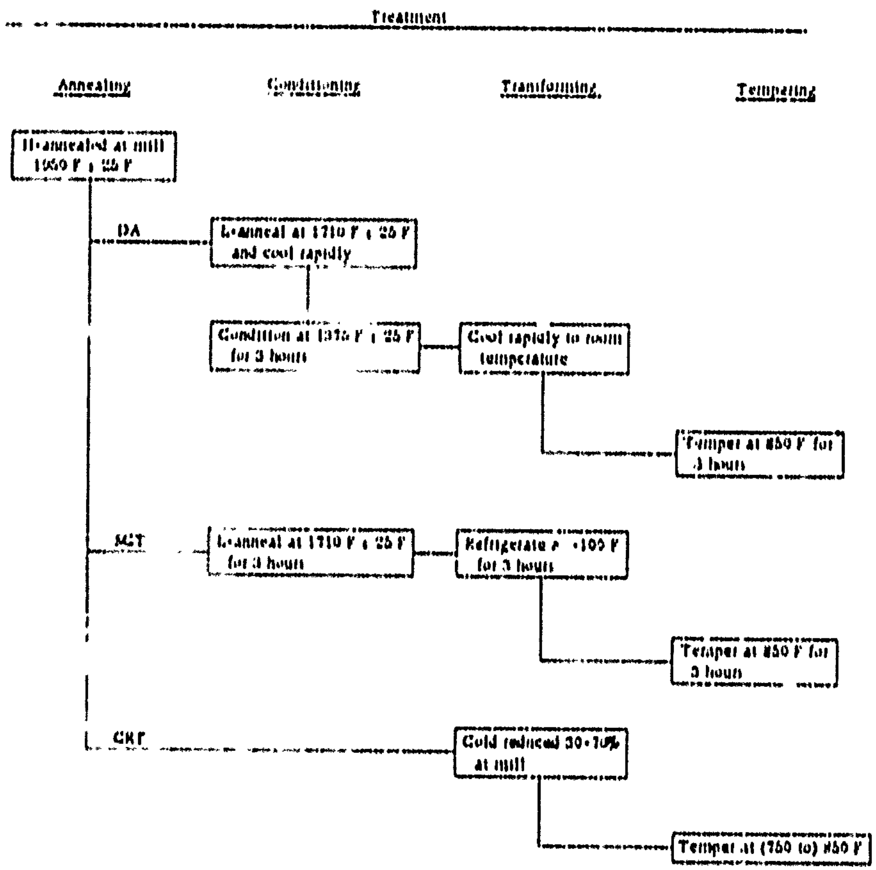
Most AM 350 is subzero cooled and tempered. This sequence of treatments yields the best combination of formability as annealed and strength as hardened.

Very little AM 350 is double aged today. The strength level resulting from this sequence is lower than that resulting from subzero cooling and tempering. Good strength, however, can be obtained without the aid of refrigerating equipment.

Some AM 350 is sold in the cold-rolled condition. Very high final streng is obtained. Formability is limited at high-strength levels t is fair at the lower strength levels of from 150,000 to 225,000 psi yield strength.

Double Aging (DA)

As shown n Figure 4, AM 350 is double aged by conditioning at 1710 F, c nditioning again at 1375 F, cooling to room temp ature, and tempering at 850 F. Th rm



Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Designation
140	63	30	H-annealed
160	80	20	L-annealed
160	106	10	
195	155	10	DA
200	110	12	
209	170	13	SCT(850)
228	200	16	CR(30)
276	250	13	CR(50)
330	322	11	CR(70)
227	214	18	CRT(30)
272	259	12	CRT(50)
335	322	11	CRT(70)

FIGURE 4. TREATMENT AND TYPICAL PROPERTIES OF AM 350

"double aging" is a holdover from an earlier period during which the 1710 F treatment was omitted. AM 350 was then "aged" at 1375 F and then "aged" again at 850 F.

Double aging was never widely practiced. In recent years, as fabricators have equipped themselves with refrigerating gear, the practice has nearly become extinct.

Conditioning. During conditioning, chromium carbide particles precipitate at the austenite-delta ferrite interfaces in AM 350. After a treatment at 1710 F, only about 0.07 per cent carbon remains in solution. On further treatment at 1375 F all but about 0.03 per cent carbon precipitates. The depletion of chromium and carbon from the matrix raises the M_s to 350 F to 400 F, and it raises the M_f above room temperature.

The 1710 F conditioning treatment may be omitted; it is sufficient to condition AM 350 at 1375 F only. The dual conditioning treatment, however, results in more uniform and complete precipitation of carbides. Double-aged material that has received the dual conditioning treatment is typically 5000 psi stronger than double-aged material that has been conditioned at 1375 F only.

Transforming. On cooling through the range 400 F to room temperature, after a treatment at 1375 F, the austenitic portion of AM 350 transforms to martensite. This structure is neither strong nor formable. But, it can be strengthened substantially by a subsequent tempering treatment.

Tempering. Transformed AM 350 is usually tempered at 850 F for 3 hours. This treatment, as illustrated in Figure 4, results in a substantial increase in strength with no loss in ductility.

The strengthening mechanism in AM 350 has been a matter of conjecture for some time. Early evidence suggested that a high-chromium ferrite precipitated during tempering. The transformation of retained austenite on cooling from tempering has also been suggested. The most recent, and best documented, work indicates that an intermetallic compound precipitates coherently from the martensite and delta ferrite during tempering. The compound has tentatively been identified as a chromium nitride.

Some typical properties of AM 350 in the double-aged condition are shown in Figure 4; others may be found in Appendix A-1.

Dimensional Changes. The transformation of austenite to martensite in stainless steels is accompanied by an expansion of about 0.005 inch/inch. For example AM 350, during treatment from the H-annealed condition to the double-aged condition, expands about 0.0048 inch/inch in the longitudinal direction and about 0.0050 inch/inch in the transverse direction. (If the L-anneal is omitted from the double-aging sequence transformation is not quite so complete and the expansion is about 10 per cent smaller.) These are net figures; they include a 0.0001 to 0.0002 inch/inch contraction on tempering. Dimensional changes must be taken into account in the design of fabricating operations.

Subzero Cooling and Tempering (SCT)

As shown in Figure 4, the subzero-cooling and tempering sequence involves a conditioning treatment at 1710 F, refrigeration at -100 F, and tempering at 850 F. Most AM 350 sold today is treated in this way. An excellent combination of formability as annealed, strength as hardened, and corrosion resistance can be had. Very few fabricators lack the refrigeration equipment necessary for this sequence of treatments.

Conditioning. If austenite is to be transformed to martensite by subzero cooling, the range of transformation temperatures must first be adjusted so that complete transformation can be obtained. This is accomplished by L-annealing, i.e., holding for a short time at 1710 F. During this treatment about 0.07 per cent carbon is retained in solution; the balance precipitates in the form of chromium carbide particles. The precipitate forms primarily at the austenite-delta ferrite interfaces. In material cold worked subsequent to the H-anneal, however, precipitation may also occur within the austenite grains wherever martensite was formed during deformation along the traces of active slip planes. The reduction in the chromium and carbon dissolved in the austenite results in an increase in M_s to a value just above room temperature, and an increase in M_f to a value above -100 F.

L-annealed AM 350 is substantially austenitic, but it contains some fresh martensite, delta ferrite, and precipitated carbides. Some typical properties are given in Figure 4. Although L-annealed AM 350 has a low yield strength, and is moderately formable, it work hardens very rapidly.

Transforming. L-annealed AM 350 is transformed by cooling it to -100 F and holding it at that temperature for 3 hours. It is unwise to take liberties with this treatment. Some technologists, unfamiliar with advances in our knowledge of the martensite reaction during the past decade or so, have refrigerated AM 350 at -320 F "to insure complete transformation". They have been rudely awakened. Transformation after treatment at -320 F is much less complete than after treatment at -100 F. Likewise failure to hold the material at -100 F for a full 3 hours may result in less than complete transformation. Although a major portion of the transformation of austenite to martensite occurs on cooling to -100 F, the reaction continues with time at -100 F.

Some typical properties of transformed material are shown in Figure 4. AM 350 conditioned at 1710 F and transformed at -100 F is slightly stronger than material conditioned at 1375 F and transformed at room temperature because of the higher carbon content of its martensite.

Tempering. Subzero-cooled AM 350 is tempered at 850 F for 3 hours. This treatment increases yield strength substantially without decreasing elongation. Some typical properties of AM 350 in the subzero-cooled and tempered (SCT) condition are shown in Figure 4; others are given in Appendix A-2.

Dimensional Changes. During transformation at -100 F, AM 350 expands; it then contracts slightly on tempering. The total dimensional change, in both the longitudinal and transverse directions, averages 0.0047 inch/inch.

Cold Rolling and Tempering (CRT)

The cold rolling and tempering sequence of treatments was designed for applications that do not require a high degree of formability and where joining methods such as spot welding or adhesive bonding can be used. The advantages under these conditions are dimensional stability, low fabricating costs, and good surfaces typical of cold-rolled materials. In addition, higher strength and a better combination of mechanical and corrosive properties are obtained by this processing method than are attainable through heat treatment alone. When very high strength, i. e., over about 225,000 psi yield strength is required, AM 355 or AM 357 are ordinarily recommended.

Transforming. AM 350 can be purchased from the mill as cold rolled or cold rolled and tempered. Based upon bend data, tempered material should have somewhat better formability although the yield is higher. No conditioning is required prior to cold rolling; severe deformation alone forces the austenite to transform to martensite. As the degree of deformation increases, the extent of the transformation increases. Some typical properties of severely deformed AM 350 are shown in Figure 4.

Tempering. Tempering at 750 to 850 F is the only thermal treatment performed by the fabricator on cold-rolled AM 350. If already tempered at the mill, a retemper is recommended both as a stress-relieving treatment and to temper the fresh martensite produced by forming. This treatment increases toughness without reducing strength or elongation.

As shown in Figure 4, cold-rolled and tempered AM 350 is very strong. The entire carbon content is effective in strengthening martensite; none is lost from solution by a conditioning treatment. In addition, cold rolling itself produces a stronger martensitic matrix than is possible through thermal treatments alone.

Some additional properties of cold-rolled and tempered AM 350 are given in Appendix A-3.

Dimensional Changes. Cold-rolled AM 350 undergoes a contraction of about 0.0001 inch/inch during tempering.

Fabrication

The fabricating procedures used for annealed AM 350 are very similar to those used for AISI 301. AM 350, however, has a higher work-hardening rate than AISI 301. This must be taken into account in any operation involving mechanical deformation. In addition, it is important to allow for dimensional changes in the design of forming operations. Some specific fabricating operations, and their interaction with thermal treatments, are described in the following paragraphs.

Cutting. AM 350 cuts like AISI 301. The shearing, punching, slitting, sawing, disk-cutting, and flame-cutting characteristics of the two steels are quite similar. In general, the cutting procedures used for AISI 301 can be specified for AM 350.

Machining. AM 350, being principally a sheet and strip product, is seldom machined. When it must be machined, however, the same practices used for other stainless steels should be observed. These include rigid tool and work support, low speeds, deep feeds, and positive cooling.

H-annealed AM 350 is soft and gummy. It is difficult to machine. Transformed material is harder, but easier to machine. With cemented carbide tools, speeds of 150 to 250 surface feet per minute and feeds of 0.004 to 0.008 inch per revolution result in good tool life on hardened material.

When close tolerances are required it is necessary either to allow for dimensional changes during heat treatment or to complete machining on fully hardened material.

Forming. AM 350 is most easily formed when it is in the H-annealed condition. It has the characteristics of AISI 301, but a somewhat higher work-hardening rate. Formability can be enhanced by heating AM 350 to 300 F.

Material trigger annealed at 1710 F can be transformed by stretching 8 to 10 per cent. Thereafter it need not be refrigerated; it can be tempered directly. One advantage of this technique is that growth during transformation is absorbed during the forming operation. But, for a uniformly hardened part, stretching must be uniform.

Transformed or fully hardened material is martensitic; it has only limited formability.

Cleaning. Before annealing it is essential that the surfaces of AM 350, or of any stainless steel, be cleaned thoroughly. Lubricants, for example, can break down at elevated temperatures and cause contamination or even corrosion. Fingerprints too can cause these problems. At best, scale will be difficult to remove if surfaces are not thoroughly cleaned prior to heat treatment.

The cleaning method recommended for AM 350 is immersion in an alkaline bath. Aqueous solutions of the orthosilicate, carbonate, hydroxide, or trisodium phosphate types are very effective. Because they emulsify oils, they are better degreasers than are organic solvents. Following cleaning, a thorough hot-water rinse should carry away all traces of the cleaner.

An optional additional treatment is immersion of cleaned work in hot dilute nitric acid. This removes the last traces of surface contaminants. The acid treatment, again, should be followed by a hot-water rinse. All work should be dry before it is placed in the furnace.

Annealing. AM 350 should be H-annealed or L-annealed for 45 to 90 minutes per inch of thickness and then cooled rapidly. Air cooling is rapid enough to prevent carbide precipitation in H-annealed sheet material. Oil or water quenching is recommended for heavy sections.

Annealing in air is entirely satisfactory in most cases. The scale formed can be removed by standard procedures. If bright annealing is required, as for foil, atmospheres of hydrogen, helium, argon, or carbon monoxide-carbon dioxide can be used. Vacuum annealing, too, produces a bright surface. Cracked ammonia should never be used; it can nitride AM 350 and alter its mechanical properties.

Descaling. Scale should be removed between intermediate anneals. A double scale is very difficult to remove, and, excessive etching of the metal may occur due to the required long exposure to the acid bath.

High-temperature scales are removed readily in a 15 per cent nitric acid-2 per cent hydrofluoric acid bath at 130 F. Pickling time should be as short as possible; usually 2 to 3 minutes will suffice. Heavy scales may require a somewhat longer pickle or a slightly increased concentration of hydrofluoric acid in the bath.

Mechanical scale-removal techniques are recommended for material that has been conditioned at 1375 F.

The tarnish formed during tempering can usually be removed by a 30-second immersion in the nitric-hydrofluoric acid solution.

Welding. AM 350 may be welded by any of the processes suitable for austenitic stainless steels. The inert-gas-shielded arc-welding methods, however, are especially well suited to this steel. Material is usually welded in the H-annealed condition, the weld metal being hardened along with the base metal during subsequent thermal treatments. Hardened structures may also be arc welded, but must be made austenitic, transformed, and tempered subsequently if joint efficiencies of 90 to 95 per cent are to be obtained. An advantage of welding fully hardened material is the reduced over-all dimension change on subsequent rehardening.

Material may be resistance welded in the hardened condition; or, it can be resistance welded in the H-annealed condition and then hardened. Either sequence of welding and hardening results in high tension and shear strengths.

Brazing. AM 350 is well suited to brazing. It contains no highly oxidizable or volatile elements to interfere with the brazing process. The steel is usually brazed with alloys that have a flow point of 1800 F or greater. After brazing, the steel is cooled directly to the conditioning temperature, 1710 or 1375 F. Thereafter it is transformed and finally tempered. Even when cooling from the conditioning treatment is slow, mechanical properties closely approach these of normally treated material.

AM 355

AM 355 is a higher-carbon, lower-chromium modification of AM 350 developed and produced by Allegheny-Ludlum Steel Corporation. Like AM 350, it is a semi-austenitic precipitation-hardenable stainless steel. AM 355 is produced in almost all wrought commercial forms, as well as castings. Typical uses are similar to those of AM 350.

AM 355 bears the following AMS designations:

AMS 5547 – Sheet and strip

AMS 5549 – Plate

AMS 5743 – Bars, forgings, and forging stock

AMS 5780 – Welding wire

AMS 5781 – Coated welding electrodes, seamless tubing.

Composition

AM 355 is a delicately balanced medium-carbon, chromium-nickel stainless steel. It is identical to AM 350 in composition except in that it contains about 0.04 per cent more carbon and about 1.0 per cent less chromium. These differences, slight as they may seem, account for some significant changes in structure. For example, AM 350 has 5 to 20 per cent delta ferrite; AM 355 usually has little or none.

The complete composition of wrought AM 355 is given below.

Element	Composition (Wrought), per cent		
	Range	Nominal	Actual Example[a]
Carbon	0.10-0.15	0.14	0.14
Manganese	0.50-1.25	0.75	0.72
Phosphorus	0.04 max	--	
Sulfur	0.03 max	--	
Silicon	0.50 max	0.30	0.29
Chromium	15.00-16.00	15.50	15.41
Nickel	4.0-5.0	4.25	4.51
Molybdenum	2.5-3.25	2.75	2.70
Nitrogen	0.07-0.13	0.10	0.11
Iron	Balance	Balance	Balance

(a) Heat No. 3 [illegible]

Cast AM 355 is leaner in the principal alloying elements than is wrought AM 355. Castings are not homogenized by working. Therefore, their composition must be adjusted so that even those portions richest in alloy content will respond to heat treatment. The complete composition of cast AM 355 is given below.

Element	Composition (Cast), per cent Range	Nominal	Actual Example[a]
Carbon	0.08-0.12	0.10	0.10
Manganese	0.75-1.10	0.90	0.98
Phosphorus	0.04 max	--	--
Sulfur	0.03 max	--	--
Silicon	0.45-0.75	0.60	0.55
Chromium	14.50-15.50	15.00	14.91
Nickel	3.50-4.50	4.20	4.30
Molybdenum	2.00-2.60	2.30	2.25
Nitrogen	0.07-0.11	0.09	0.11
Iron	Balance	Balance	Balance

(a) Heat No. 6796.

Availability

AM 355 is commercially available in a wide variety of forms. Flat rolled products are supplied either as solution heat treated or as solution heat treated and cold rolled. The same dimensions of flat rolled stock listed earlier for AM 350 also apply to AM 355. Bar products are usually supplied in the equalized and overtempered condition for best machinability. Castings are usually supplied in the as-cast condition.

Treatment of Sheet

When AM-355 is to be double aged or conditioned, subzero cooled, and tempered, it is solution heat treated at either 1950 F ± 25 F or 1875 F ± 25 F. The latter treatment can be followed directly by the hardening heat treatments to obtain high strength while the former requires about 25 per cent cold deformation prior to the hardening treatments in order to obtain maximum strength. The reader may recall that AM-350 is solution heat treated at 1950 F ± 25 F but does not require the cold deformation for proper response to the hardening heat treatments. AM-350 contains a small percentage of delta ferrite which restricts grain growth during solution heat treating. In addition, the austenite-delta ferrite interfaces in AM-350 provide sites for carbide precipitation during the conditioning treatment at 1710 F. This results in a more uniform carbide distribution which in turn results in a more uniform transformation of austenite to martensite during the subzero cooling. AM-355 does not contain delta ferrite. However, by solution heat treating at 1875 F, not all primary carbides are taken into solution. These carbides provide sites for further carbide precipitation during conditioning. Solution heat treating of AM-355 at 1950 F results in grain growth and solution of carbides. Upon conditioning at 1710 F, the carbides precipitate in the grain boundaries and, upon subzero cooling, a considerable amount of the austenite does not transform to martensite. Cold deformation of AM-355 solution heat treated at 1950 F results in partial transformation to martensite and the formation of active slip planes, both of which provide excellent sites for carbide precipitation during subsequent conditioning.

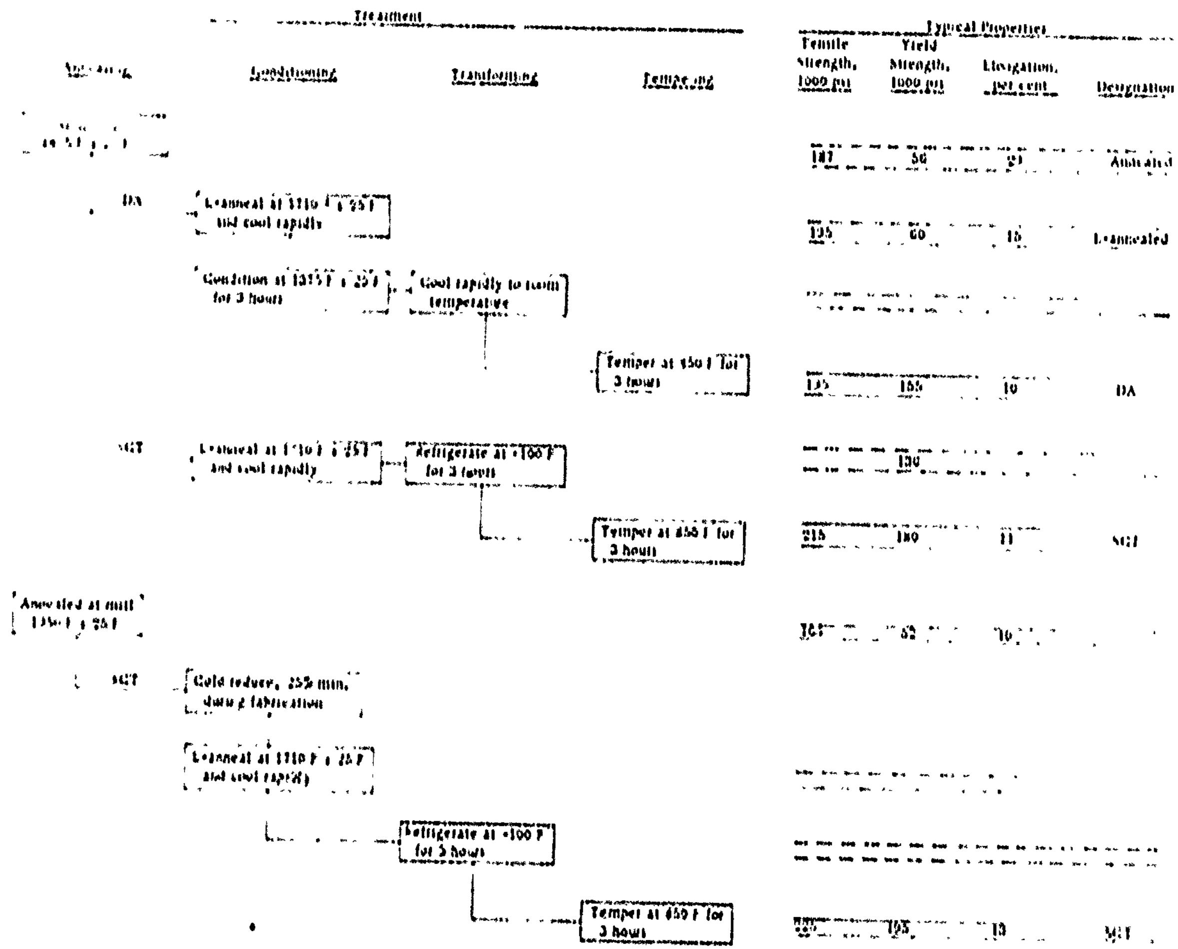
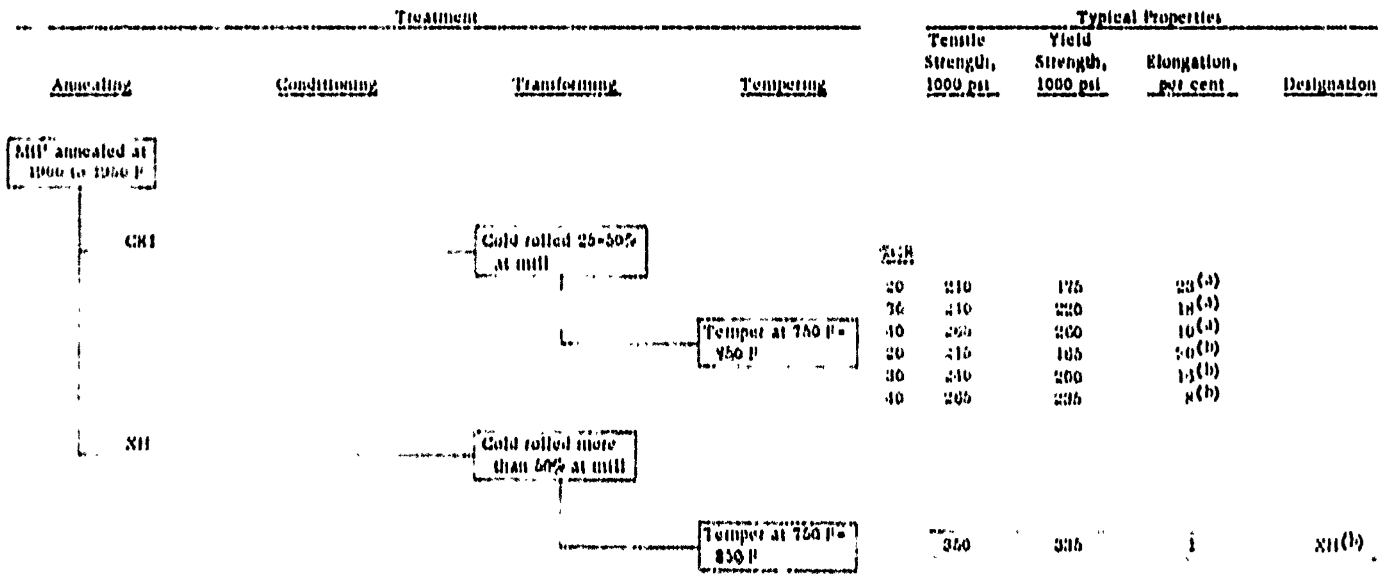


FIGURE 5. TREATMENT AND TYPICAL PROPERTIES OF AM 355 SHEET



(a) Longitudinal
(b) Transverse

FIGURE 5. (CONTINUED)

AM-355 solution heat treated at 1950 F ± 25 F is soft, entirely austenitic, and in the best condition for forming. It has an Ms between 0 and -100 F. AM-355 solution heat treated at 1875 F ± 25 F is relatively soft and, with the exception of some undissolved carbides, is generally austenitic. It has an Ms between 0 and 100 F. Thus, appreciable hardening can occur in the latter during storage and transit. Primarily for this reason, AM-355 is supplied commercially only in the 1950 F ± 25 F solution heat treated condition. As noted previously, AM-355 in this condition requires about 25 per cent cold deformation prior to the hardening heat treatments in order to obtain maximum strength. The cold deformation may be supplied by a forming operation, but must be accomplished in all areas to insure uniform response to the hardening heat treatments. However, if a part requires a number of successive forming operations and anneals, limitation of the intermediate annealing temperature to 1875 F by the fabricator will result in proper response to hardening heat treatments.

When AM-355 is sold in the cold rolled condition, it has been solution heat treated at 1900 F to 1950 F prior to cold rolling and usually tempered at 800 F to 850 F subsequent to cold rolling. The desired strength is controlled by the amount of cold reduction. While strength can also be controlled by selection of anneal temperature between 1750 F and 1950 F, the high anneal is more desirable because it results in a better combination of mechanical and corrosion properties and a more uniform structure. All carbon is in solution, and the structure consists of tempered martensite and austenite.

After solution heat treatment at 1875 F or solution heat treatment at 1950 F followed by about 25 per cent cold deformation, AM-355 may be double aged or conditioned, subzero cooled, and tempered. These treatments are diagramed in Figure 5. A small portion of the AM-355 sold is subzero cooled and tempered; very little is double aged.

The major portion of AM-355 is sold in the solution heat treated, cold rolled, and tempered condition (CRT), while some is used in the extra hard condition (XH). Again these sequences of treatments are diagrammed in Figure 5; they are detailed in the following paragraphs.

Double Aging (DA)

As shown in Figure 5, AM-355 annealed at 1875 F can be hardened by conditioning first at 1710 F, then at 1375 F, and finally tempering at 850 F. Conditioning at 17 0 F is not required for AM-355 annealed at 1950 F and cold deformed about 25 per cent. This sequence of treatments is used only rarely for AM-355 because other treatments provide greater strength. Nevertheless, double aging has proved useful in some isolated instances.

Conditioning. AM-355 annealed at 1875 F contains undissolved carbides which provide active sites for carbide precipitation on subsequent conditioning at 1710 F. After continued conditioning at 1375 F for three hours, only about 0.03 per cent carbon remains in solution. The depletion of carbon and chromium from solid solution raises the M_s and M_f and thereby triggers the matrix for transformation on cooling. While the 1710 F treatment is mandatory in the case of AM-355 annealed at 1875 F, it is not necessary for AM-355 annealed at 1950 F and cold deformed about 25 per cent.

Transforming. AM-355 conditioned at 1375 F with the proper prior treatments becomes martensitic on cooling to room temperature.

Tempering. Transformed AM 355 is tempered at 850 F for 3 hours. The same strengthening mechanism active in AM 350 is also thought to harden AM 355 during tempering. Both AM 350 and AM 355 in the double aged condition have about the same properties. These are shown in Figure 5. Some additional properties of AM 355 in the double-aged condition are given in Appendix B-1.

Dimensional Changes. AM 355 expands significantly when it is martensitized, and contracts slightly when tempered. From the 1875 F annealed condition to the double-aged condition AM 355 expands 0.0059 inch/inch in the longitudinal direction and 0.0054 inch/inch in the transverse direction. These figures include a contraction of about 0.0002 inch/inch. The net expansion is greater for AM 355 than for AM 350. In AM 355 nearly the entire structure transforms and thus expands. In AM 350 the 5 to 20 per cent of the matrix composed of delta ferrite takes no part in transformation and contributes nothing toward expansion.

Subzero Cooling and Tempering (SCT)

As shown in Figure 5, AM 355 can be hardened by conditioning at 1710 F, refrigerating at -100 F, and tempering at 850 F after solution treatment at 1875 F. This sequence combines good formability in the annealed condition with good strength and corrosion resistance in the hardened condition. But, subzero-cooled and tempered AM 355 lacks the very high strength that can be obtained in cold-rolled material.

Conditioning. AM 355 destined to be subzero cooled and tempered is L-annealed at 1710 F. This conditioning treatment allows about 0.07 per cent carbon to remain in solution; the balance precipitates as chromium carbide particles at grain boundaries and around previously undissolved carbides. The M_s is raised to about 160 F. Thus, on cooling to room temperature, some martensite forms.

L-annealed AM 355, being partially austenitic, retains some formability. Typical properties are given in Figure 5.

Transforming. L-annealed AM 355 is transformed by cooling it to -100 F and holding it at that temperature for 3 hours. Normally this operation is carried out in cold boxes that are commercially available in a wide variety of sizes. A mixture of dry ice and methanol, however, serves equally well for small or experimental work when a cold box is not available.

Tempering. Subzero-cooled AM 355 sheet is tempered at 850 F for 3 hours. Some typical properties of AM 355 in the subzero-cooled and tempered condition are shown in Figure 5; others are given in Appendix B-2.

Modified SCT Treatment. As received from the mill with a 1950 F solution heat treatment, AM 355 requires about 25 per cent cold deformation during fabrication prior to hardening by conditioning, subzero cooling, and tempering. The 1950 F anneal results in complete solution of carbides and large grains and in enhanced ductility. The martensite and slip planes formed during subsequent deformation serve as sites for carbide precipitation during conditioning at 1710 F.

Dimensional Changes. AM 355 undergoes an average net expansion of 0.0058 inch/inch in the longitudinal direction and 0.0062 inch/inch in the transverse direction during treatment from the H-annealed condition to the subzero-cooled and tempered condition.

Cold Rolling and Tempering (CRT)

Most AM 355 is sold in the cold-rolled and tempered condition. Cold-rolled material lacks the good formability of 1950 F annealed material, but an excellent variety of high strength levels can be obtained. Elongation, for a given strength level, is better than can be obtained by thermal treatments alone.

Transforming. AM 355, after a mill anneal at 1900 to 1950 F, can be transformed by cold rolling. No conditioning is required. The greater the degree of reduction the greater the extent of transformation. A variety of final strength levels can be obtained by regulating the degree of cold reduction between 25 and 50 per cent.

Tempering. Tempering of cold-rolled AM 355 at 750 to 850 F is usually done in the mill. After forming, the fabricator may find it desirable to retemper. Some typical property combinations of cold-rolled and tempered AM 355 are shown in Figure 5; others are given in Appendix B-3.

Dimensional Changes. Cold-rolled AM 355 undergoes a contraction of about 0.0001 inch/inch during tempering.

Extrahardening (XH)

It is possible to obtain extremely high strengths in AM 355 by a sequence of treatments analogous to the CRT sequence. Instead of cold rolling material 25 to 50 per cent, however, the mill extrahardens AM 355 by cold rolling it more than 50 per cent (usually 55 per cent). Exceptionally high strengths can be obtained. Some typical properties of extrahard AM 355 are shown in Figure 5; others are given in Appendix B-4.

Subzero Cooling, Cold Rolling, and Tempering (SCCRT)

AM 355 is not marketed in the SCCRT condition. This treatment is discussed only to show the properties that can be obtained by this sequence of treatments. The subzero-cooling, cold-rolling, and tempering sequence of treatments is used when the high strength of cold-rolled AM 355 is desired in the thicker sheet sections. By effecting a portion of the transformation thermally, and the balance by cold rolling, high strengths can be obtained with a smaller degree of cold rolling. For example, if 0.100-inch-thick hot band is the starting stock for the cold rolling mill, 50 per cent reduced CRT material would be only 0.050 inch thick. But, if the hot band is first partially transformed by thermal means, it may be possible to obtain complete transformation by cold rolling only 25 per cent. Final SCCRT stock 0.075 inch thick could thus be obtained.

Transforming. In the SCCRT sequence, transforming is a two-step mill operation. After a solution-trigger treatment, usually at 1800 F, AM 355 is partially transformed by refrigeration at -100 F for 3 hours. The transformation is completed by cold rolling 20 to 30 per cent. Actually, the major portion of the transformation occurs during refrigeration.

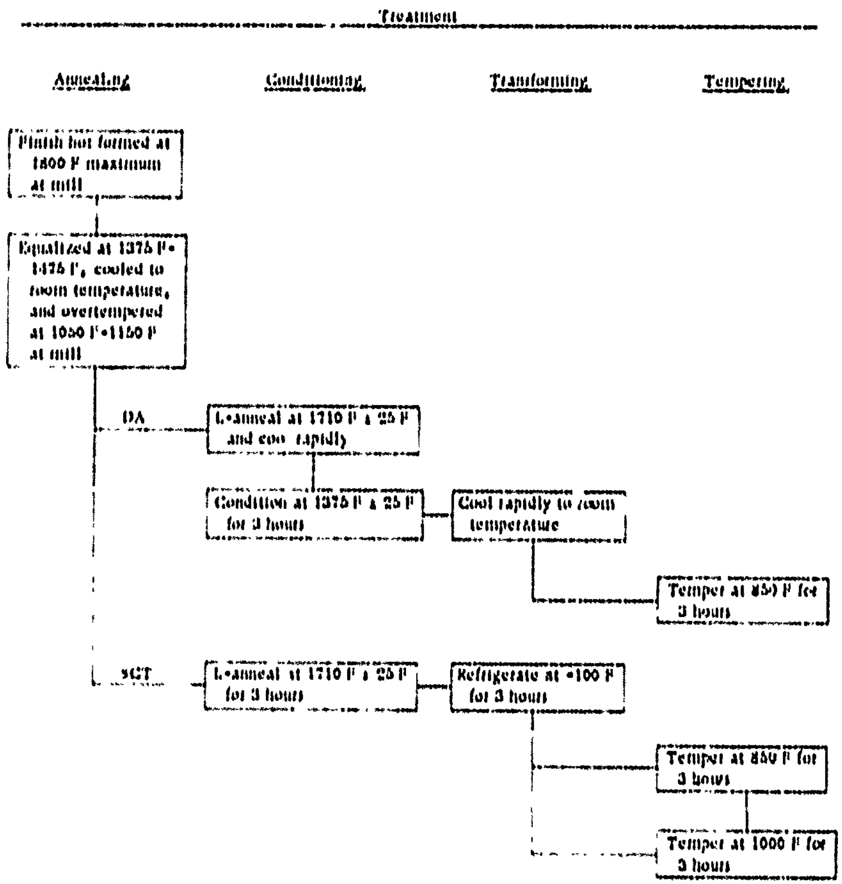
Tempering. Subzero-cooled and cold-rolled AM 355 is tempered at 750 to 850 F to obtain the final properties illustrated in Figure 5. Additional properties may be found in Appendix B-5.

Subzero-cooled, cold-rolled, and tempered (SCCRT) AM 355 possesses the high strength of material transformed by cold rolling alone. Yet, because it has been cold worked only moderately, it retains much of the isotropy of material hardened by thermal treatments alone.

Dimensional Changes. Subzero-cooled and cold-rolled AM 355 undergoes a contraction of about 0.0001 inch/inch during tempering.

Treatment of Bar

AM 355 bar stock is heat treated somewhat differently than are sheet products. Bars are more often machined than formed. Therefore, heat treatments are designed to provide the best machinability rather than the best formability. Rather than being H-annealed, bars are hot worked to size and finished at a maximum of 1800 F to produce a fine-grained structure. Subsequent equalization at 13[illegible] to 1475 F for 3 hours plus cooling to room temperature results in a homogeneous structure of chromium carbides in a low-carbon martensite. Overtempering at 1050 to 1150 F then produces the structure that is the most machinable. If machining operations are not planned, of course, the overtempering treatment may be omitted. Bars are marketed in either the equalized or the equalized and overtempered condition.



Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Designation
167	130	18	E + O
			L-annealed
185	150	16	DA
215	180	10	SCT (850)
185	170	19	SCT (1000)

FIGURE 6. TREATMENT AND TYPICAL PROPERTIES OF AM 355 BAR

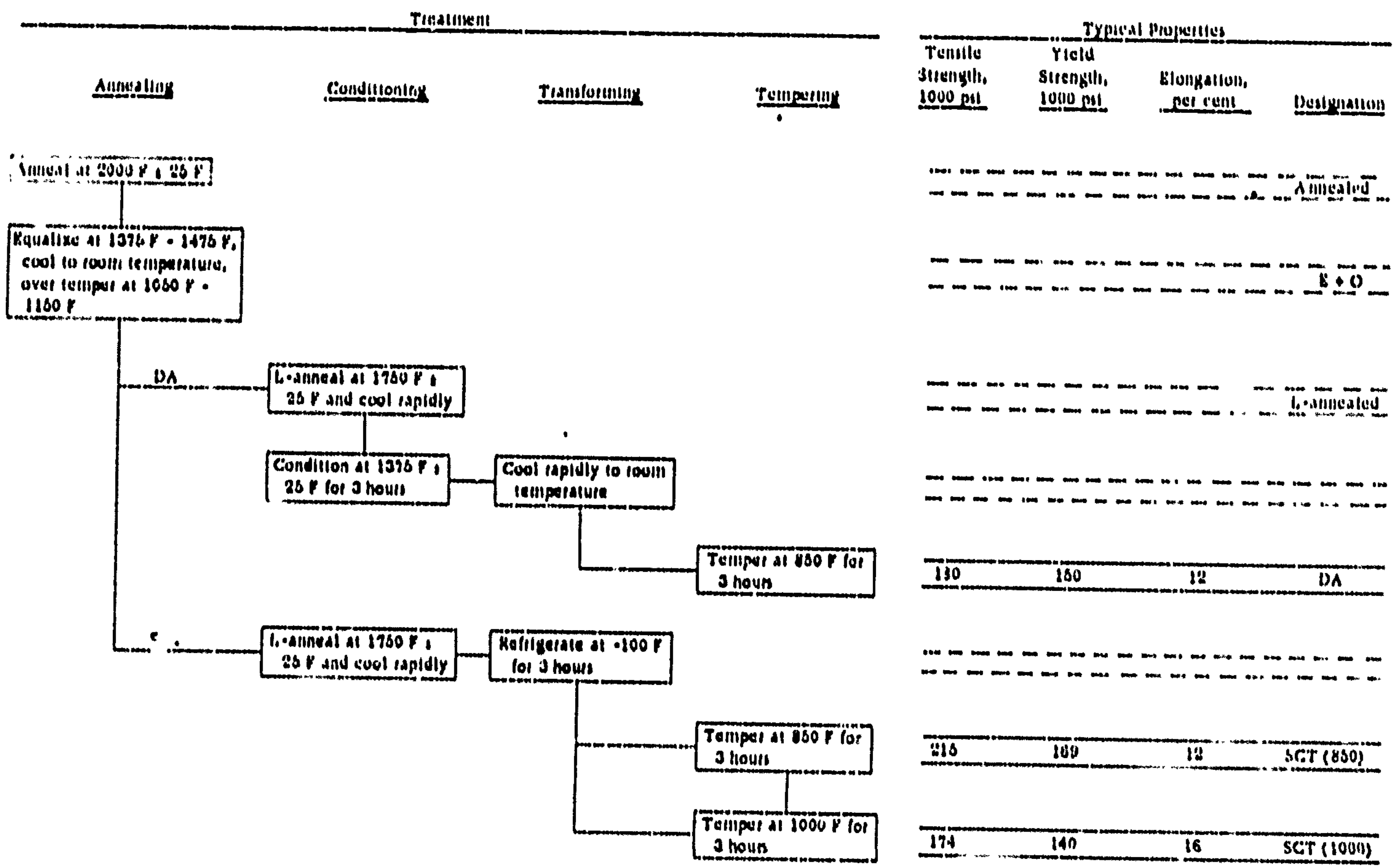


FIGURE 7. TREATMENT AND TYPICAL PROPERTIES OF AM 355 CASTINGS

As shown in Figure 6, AM 355 bar may be hardened in the same manner as sheet either by the DA sequence or by the SCT sequence of treatments. Double aging is seldom used on AM 355 bar; most is subzero cooled and tempered. When improved toughness is desired, and some reduction in strength can be tolerated, subzero-cooled AM 355 bar may be tempered at 1000 F rather than at 850 F.

Some illustrative properties of AM 355 bar are presented in Figure 6; others may be found in Appendices B-1 and B-2.

Treatment of Castings

As shown in Figure 7, the treatment of AM 355 castings is very similar to the treatment of bar. But, castings lack the homogenizing effects of either hot or cold work. Therefore they must be annealed at 2000 F to minimize coring. Thereafter castings are treated the same as bars, with the exception that they are L-annealed at 1750 F rather than 1710 F.

Some illustrative properties of AM 355 castings are given in Figure 7; others may be found in Appendices B-1 and B-2.

Allegheny-Ludlum does not sell castings itself, but licenses a number of foundries to produce and sell AM 355 castings.

Fabrication

The fabrication characteristics of AM 355 are almost identical to those of AM 350. Special treatments, i.e., equalizing and overtempering, however, have been devised to provide good machinability in AM 355.

AM 357

AM 357 is a semiaustenitic precipitation-hardenable stainless steel developed, and produced in pilot quantities, by Allegheny-Ludlum Steel Corporation. It is a high-carbon, low-chromium modification of AM 355. Although AM 357 responds to heat treatment in the same manner as AM 355, it offers little advantage over AM 355 when it is hardened by thermal treatments alone. This steel was developed specifically to be hardened to very high strength levels by combinations of thermal and mechanical treatments. When hardened in this way AM 357 has a better combination of strength and residual ductility than can be obtained with AM 355.

Composition

AM 357 is a high-carbon semiaustenitic precipitation-hardenable stainless steel. Whereas other semiaustenitic stainless steels normally contain about 0.10 per cent, AM 357 usually contains about 0.25 per cent carbon. To maintain the transformation characteristics of AM 350 and AM 355, however, the chromium content has been reduced to 14 per cent. The complete composition of AM 357 is given below.

Element	Composition, per cent		
	Range	Nominal	Actual Example[a]
Carbon	0.21-0.26	0.24	0.22
Manganese	0.50-1.25	0.75	0.66
Phosphorus	0.04 max	--	--
Sulfur	0.03 max		--
Silicon	0.50 max	0.30	0.18
Chromium	13.50-14.50	14.00	14.04
Nickel	4.0-5.0	4.20	4.56
Molybdenum	2.5-3.25	2.75	2.87
Nitrogen	0.07-0.13	0.10	0.095
Iron	Balance	Balance	Balance

(a) Heat No. 9X635.

Availability

AM 357 is a developmental steel. Although a list of forms available on standard mill order has not yet been prepared, AM 357 is generally available as solution-annealed plate or annular-shaped forgings for shear forming, or as sheet in any of the cold-rolled conditions (CRT, XH, or SCCRT).

Treatment

A solution anneal at the mill is usually the first treatment applied to AM 357 sheet. This treatment, at 2000 F, takes nearly all the carbides into solution. A uniform austenitic structure is developed and is retained on rapid cooling to room temperature.

Plate purchased in the solution-annealed condition subsequently may be cold formed or ausformed and then tempered. The subzero-cooling and tempering sequence is not recommended. Both cold forming and ausforming, followed by tempering, result in extremely high strength and also high ductility. Yield strengths in excess of 300,000 psi, with residual elongation greater than 15 per cent, have been obtained. These excellent mechanical properties are unique among stainless materials.

AM 357 strip may be purchased as transformed by the mill. After the solution anneal, strip is transformed by cold rolling (CRT, XH). Very high strengths are obtained subsequently on tempering. AM 357, in any of these conditions, has a better combination of strength and ductility than does AM 355.

The treatment of AM 357 is diagramed in Figure 5.

Subzero Cooling and Tempering (SCT)

AM 357 in the subzero-cooled and tempered condition offers little advantage over AM 355 in the same condition. Therefore, AM 355 is recommended if this condition is desired. But, as shown in Figure 8, AM 357 can be hardened by the SCT sequence in the same manner as AM 355.

Some illustrative properties of AM 357 in the subzero-cooled and tempered condition are presented in Figure 8; others may be found in Appendix C-1.

Shear Forming

Solution-annealed AM 357 may be transformed at room temperature by shear forming or automatic spinning. Other forming methods that result in a large and uniform deformation, of course, may be substituted for shear forming. The strength obtained on subsequent tempering at 850 F increases with increasing amounts of forming. Very high strength, with excellent residual ductility, can be obtained.

Some illustrative properties of shear-formed AM 357 are presented in Figure 8; others are given in Appendix C-2.

Ausforming

Solution-annealed AM 357 can be transformed by working at slightly elevated temperatures (ausforming) as well as by working it at room temperature. Excellent properties have been obtained when material is deformed 75 to 90 per cent in the temperature range of from 250 to 300 F, and subsequently tempered at 850 F.

As illustrated in Figure 8, extremely high strength, coupled with excellent residual ductility, is characteristic of ausformed material. Some additional properties are given in Appendix C-3.

Cold Rolling and Tempering (CRT)

After a solution anneal at 2000 F, AM 357 can be transformed by cold rolling. The greater the degree of cold rolling, the greater the extent of transformation and the greater the strength after tempering. A variety of yield-strength levels, from about 200,000 to 300,000 psi, can be obtained by reductions of 25 to 50 per cent. Elongations range from about 20 per cent to about 5 per cent, decreasing as strength increases.

The fabricator usually purchases material in the cold-rolled and tempered condition, forms it, and retempers it at 850 F. Cold-rolled AM 357 lacks the excellent formability of solution-annealed material, but it can withstand fairly severe forming operations at the lower strength levels.

Some illustrative properties of AM 357 in the cold-rolled-and-tempered condition are shown in Figure 8; others are given in Appendix C-4. It should be noted that CRT AM 357 has better elongation at a given strength level than that of CRT AM 355. The newer steel was developed to provide both high strength and good toughness.

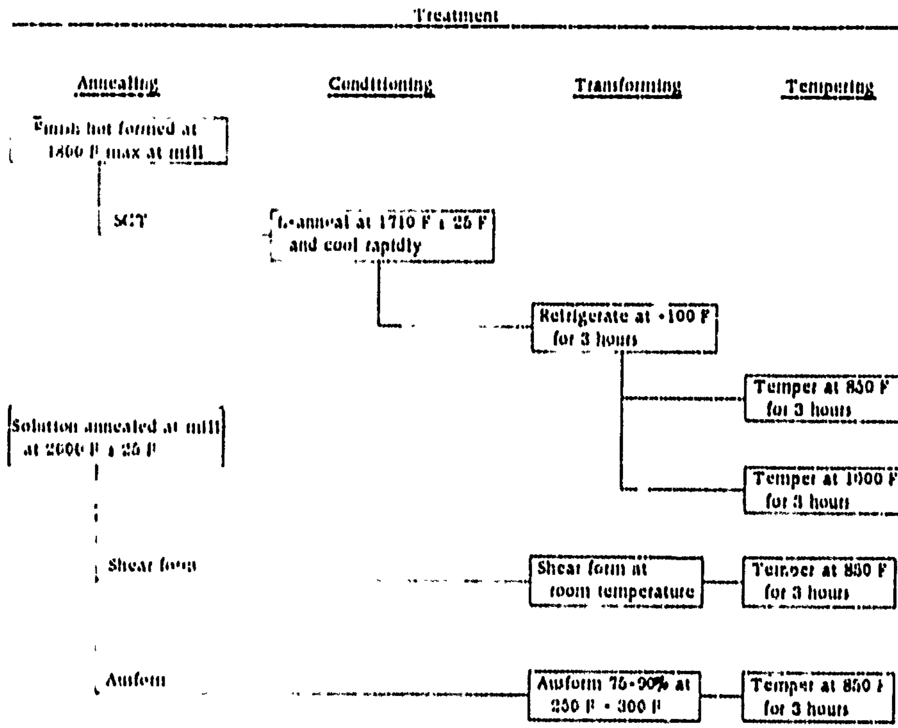
Extrahardening (XH)

Extrahardening is analogous to cold rolling and tempering. The only difference is that extrahardened material is cold rolled more than 50 per cent (usually 65 per cent); cold-rolled and tempered material is cold rolled in amounts from 25 to 50 per cent. Higher strengths, of course, can be obtained by extrahardening than by cold rolling and tempering.

Some illustrative properties of extrahard AM 357 are shown in Figure 8; others are given in Appendix C-5. AM 357, even when hardened to a yield-strength level in excess of 350,000 psi, retains measurable ductility.

Subzero Cooling, Cold Rolling, and Tempering (SCCRT)

A subzero-cooling, cold-rolling, and tempering (SCCRT) sequence of hardening treatments may also be used for AM 357. Preliminary tests indicate that yield strengths greater than 300,000 psi, with good residual elongation, can be obtained in thick sheet sections. The SCCRT sequence of treatments, together with illustrative properties is diagramed in Figure 8. Other properties are given in Appendix C-6.



Typical Properties			
Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Designation
--	--	--	Annealed
--	--	--	L-annealed
--	--	--	
234	193	15	SCT (850)
183	169	16	SCT (1000)
248	198	23	(34%)
269	262	15	([illegible])
313	312	16	([illegible])
345	320	20	(88%)

FIGURE 8. TREATMENT AND TYPICAL PROPERTIES OF AM 357

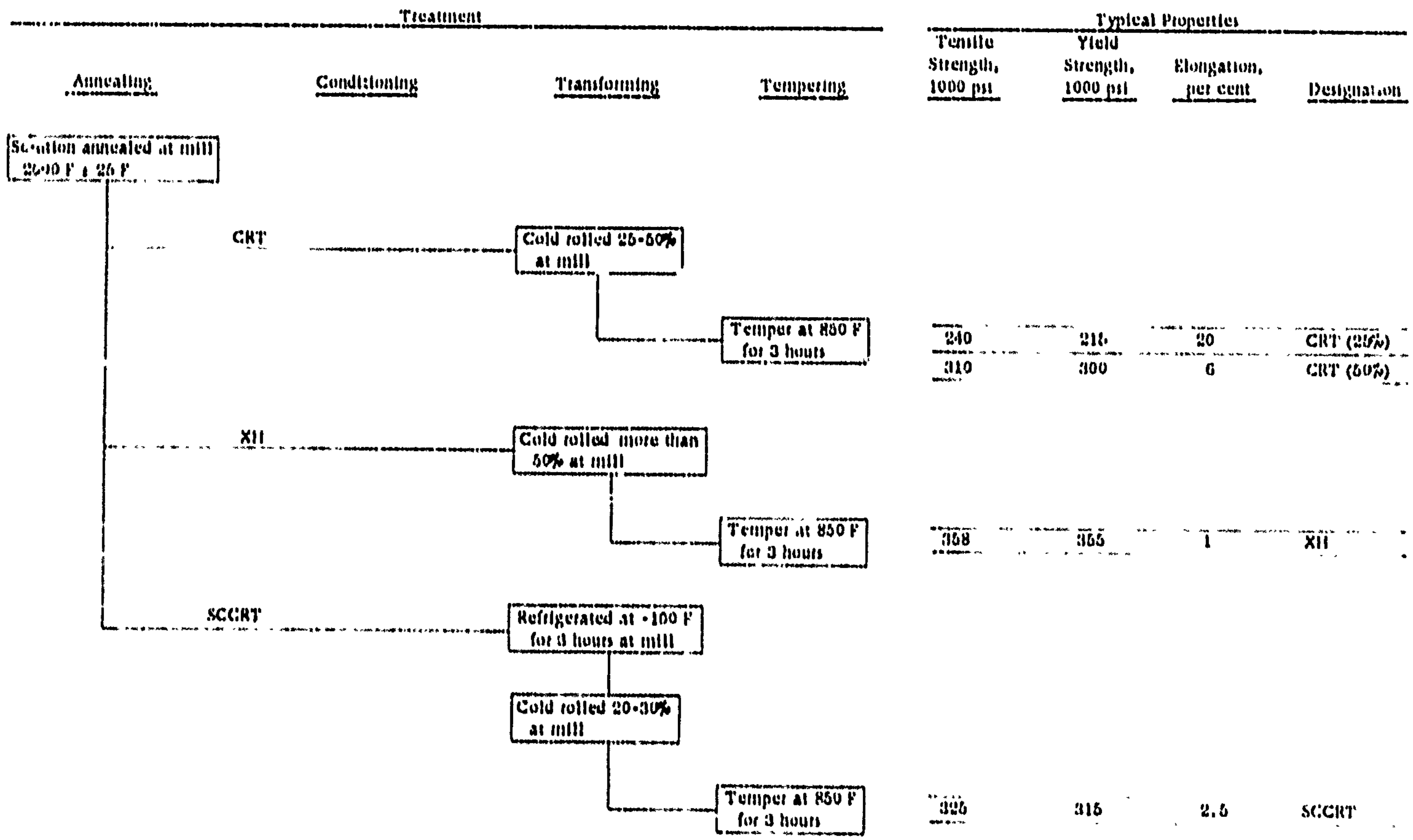


FIGURE 8. (CONTINUED)

AM 359

AM 359 is a semiaustenitic precipitation-hardenable stainless steel under development by Allegheny-Ludlum Steel Corporation. It is not commercially available. Unlike other Allegheny steels, AM 359 contains aluminum to promote precipitation hardening. The producer envisions AM 359 as a sheet and bar product to be hardened by a sequence of treatments similar to those used for AM 355.

Composition

AM 359, like AM 357, is of the high-carbon, low-chromium semiaustenitic variety. In addition, it contains the 2.75 per cent molybdenum characteristic of Allegheny's semiaustenitic stainless steels. It contains an addition of aluminum to promote precipitation hardening and increased nickel content to offset the ferrite-promoting effect of aluminum. The complete composition of AM 359 is given below.

	Composition, per cent		
Element	Range	Nominal	Actual Example[a]
Carbon	0.17-0.21	0.19	0.21
Manganese	0.50-1.25	0.75	0.50
Phosphorus	0.04 max	--	0.022
Sulfur	0.03 max	--	0.018
Silicon	0.50 max	0.30	0.25
Chromium	13.50-14.50	14.0	14.27
Nickel	6.5-7.5	7.0	6.59
Molybdenum	2.5-3.25	2.75	2.68
Aluminum	0.80-1.35	1.15	1.19
Iron	Balance	Balance	Balance

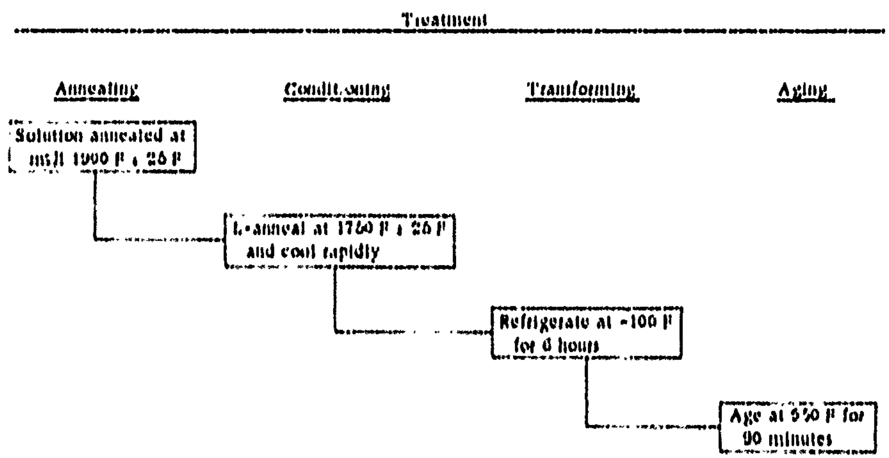
(a) Heat No. 13009.

Availability

AM 359 is available in bar and sheet form in developmental quantities from Allegheny-Ludlum Steel Corporation.

Treatment of Sheet

The treatment of AM 359 sheet, together with the resulting properties, is diagramed in Figure 9. The solution heat treatment, at 1900 F ± 25 F, takes part of the carbides into solution. The resulting homogeneous austenitic solution is retained on rapid cooling to room temperature. As shown in Figure 9, annealed AM 359 has good ductility and low yield strength. It is easily formed.



Typical Properties			
Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Designation
108	61	28	Annealed
225	224	6	SCA

FIGURE 9. TREATMENT AND TYPICAL PROPERTIES OF AM 350 SHEET

After fabrication, AM 359 is hardened by conditioning, subzero cooling, and aging. The conditioning treatment, or L-anneal, consists of a short soak at 1750 F ± 25 F. Some of the carbon precipitates in the form of chromium carbide particles, but about half of the carbon remains in solution after this treatment. The resulting depletion of chromium and carbon from solid solution raises the transformation temperature so that transformation is effected by a subsequent [illegible] tment at -100 F for 6 hours.

Final hardening of AM 359 is accom[illegible] by aging at 950 F for 90 minutes. Some illustrative properties of subzero-co[illegible] and aged (SCA) AM 359 sheet are presented in Figure 9; others may be found in Appendix D-1. SCA AM 359 is somewhat stronger than SCT AM 355.

Treatment of Bar

AM 359 bar is hardened in exactly the same manner as AM 359 sheet. Bar, however, is more often machined than formed. Therefore the initial treatment is designed to provide the best machinability rather than the best formability. As shown in Figure 10, bar is finished in the mill at a maximum temperature of 1800 F to assure a fine-grained structure. The mill then equalizes AM 359 at 1375 to 1475 F to produce a low-carbon martensite on subsequent cooling to room temperature. It is subsequently overaged at 1150 to 1250 F.

Subzero-cooled and aged AM 359 bar is somewhat stronger than subzero-cooled and tempered AM 355. Some illustrative properties of subzero-cooled and aged AM 359 bar are shown in Figure 10; others may be found in Appendix D-1.

Treatment				Typical Properties			
Mill Treatment	Conditioning	Transforming	Aging	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation per cent	Designation
Finish hot formed at 1800 F maximum at mill							
Equalized at 1375 F-1475 F, cooled to room temperature, and overaged at 1050 F-1150 F at mill				183	167	12	E + O
	Re-anneal at 1750 F ± 25 F and cool rapidly						Re-annealed
		Refrigerate at -100 F for 8 hours					
			Age at 850 F for 90 minutes	253	235	8	SCA

FIGURE 10. TREATMENT AND TYPICAL PROPERTIES OF AM 359 BAR

17-7 PH

17-7 PH is a semiaustenitic precipitation-hardenable stainless steel developed, patented, and produced by the Armco Steel Corporation. It is also produced, under license, by Republic Steel Corporation. This steel is mainly a sheet and strip product, but heavy sections are also produced.

17-7 PH bears the following AMS designations:

5528 A – Plate, sheet, and strip
5529 A – Sheet and strip
5563 – Welded tubing
5644 A – Bars and forgings
5673 A – Wire, spring temper.

It also complies with United States Air Force specifications MIL-S-25043-B and QQ-S-00766-B (Ships), Amendment 1, Class 323.

A list of typical uses of 17-7 PH follows:

Military
- Springs, bolts, pins, couplings, and valves in aircraft hydraulic units
- Aircraft sandwich panel, core and skin
- Compressor blading, shrouds, shafts, bolts, nozzles, washers, springs, and pins in aircraft engines
- Aircraft ribs and stringers
- Springs, shafts, bellows, and gears in aircraft instruments
- Aircraft structural components, ribs, stringers, engine supports
- Landing-gear assemblies
- Aircraft motor and pump parts
- Spring-loaded frames for aircraft windows

Nonmilitary
- Appliance parts
- Beverage filling machine parts
- Check valve plates
- Cheese spreaders
- Conveyor chains
- Hose clamps
- Leaf springs
- Lock washers
- Milk-packaging machinery
- Piston-ring expanders
- Pressure tanks
- Oil seals
- Hand saws
- Spatula blades
- Spring clips and flat springs

Stencil cylinders
Thermostat clickers
Valve disks and rings
Windshield-wiper parts
Retainer rings

Composition

17-7 PH is a low-carbon, 17 per cent chromium-7 per cent nickel stainless steel containing about 1 per cent aluminum to impart precipitation-hardening qualities. Its composition is given below.

Element	Composition, per cent		
	Range	Nominal	Actual Example[a]
Carbon	0.09 max	0.07	.072
Manganese	1.00 max	0.50	0.57
Phosphorus	0.04 max		0.018
Sulfur	0.04 max		0.017
Silicon	1.00 max	0.50	0.43
Chromium	16.00-18.00	17.00	17.18
Nickel	6.50-7.75	7.00	7.16
Aluminum	0.75-1.50	1.20	1.15
Iron	Balance	Balance	Balance

(a) Heat No. 810165.

Availability

17-7 PH sheet, strip, and plate in the mill-annealed condition and with a No. 1 or No. 2 finish, is available in a variety of widths. Sheet and strip cold rolled 60 per cent (Condition C) is available in gages up to 0.050 inch and widths to 36 inches. A partial listing of available forms follows:

Form	Condition	Dimensions, inches		
		Thickness	Width	Length
Sheet	A	0.010-0.014	24-36	Coil[a]
		0.015-0.125	24-44	Coil[a]
		0.010-0.014	24-36	164 max
		0.015-0.050	24-49	164 max
			44-48	144[b] max
		0.050-0.109	24-44	180[b] max
			44-48	168[b] max
			44-72	168[b] max
		0.109-0.1874	24-72	216[b] max

Form	Condition	Dimensions, inches: Thickness	Width	Length
Sheet	C	0.010-0.050	24-36	Coil[a]
Strip	A	0.010-0.125	1-23-15/16	Coil[a]
	A and C	0.0015-0.00299	1/4-12	Coil[a]
		0.003-0.010	1/4-16	Coil[a]
Plate	A	3/16-1/4	6-72	204 max
		17/64-5/16	6-36	180 max
			36-48	156 max
			48-66	144 max
			66-78	132 max
		11/32-3/8	6-36	156 max
			36-42	144 max
			42-48	132 max
			48-72	120 max
		13/32-1/2	6-36	120 max
			36-72	84 max

(a) Also available in cut lengths to 164 inches. Other forms and dimensions may be available on special order.

(b) Maximum lengths for some thicknesses and widths are less than shown.

Treatment

17-7 PH is usually purchased in Condition A. It is solution heat treated at the mill at 1950 F to develop this condition. During the treatment carbides are dissolved and aluminum is homogeneously distributed throughout the matrix. On cooling, the austenitic structure (with 5 to 20 per cent delta ferrite) developed at the high temperature is retained. Material in Condition A is austenitic, soft, and formable. Some typical properties of 17-7 PH in Condition A are given in Figure 11.

Variations in annealing temperature, within rather wide limits, have little affect on the properties of material in Condition A. But, they have a significant affect on material subsequently hardened. Annealing temperatures much in excess of 1950 F decrease strength and ductility. Temperatures much lower than 1950 F, while they may increase strength, lower ductility. Little change in properties, however, is noted as a result of variations within the prescribed 1950 F ± 25 F range.

17-7 PH is usually fabricated in Condition A. Thereafter it can be hardened, by thermal treatments alone, by one of the first three sequences diagrammed in Figure 11.

Treatment				Typical Properties			
Annealing	Conditioning	Transforming	Aging	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Designation
Mill annealed 1950 F ± 25 F				130	40	35	A
TH	Heat to 1400 F ± 25 F, hold for 90 minutes	Cool to 60 F $^{+0}_{-10}$ F within 1 hour, hold for 30 minutes		145	100	[illegible]	T
			Heat to 1050 F ± 10 F, hold for 90 minutes, air cool to RT	200	185	9	TH 1050
RH	Heat to 1750 F ± 15 F, hold for 10 minutes, air cool to RT			130	42	30	A-1750
		Within 1 hour start cooling to -100 F ± 10 F, hold for 8 hours		175	115	[illegible]	R-100
			Heat to 950 F ± 10 F, hold for 60 minutes, air cool to RT	225	220	6	RH 950
			Hold at 950 F ± 10 F, 2 hours plus 900 F ± 10 F, 3 hours plus 850 F ± 10 F, 3 hours	250	235	[illegible]	[illegible]
LH	Heat to 1825 F ± 15 F, hold for 2 hours, air cool to RT	Cool to -100 F ± 10 F, hold for 8 hours					L
			Heat to 950 F ± 10 F, hold for 60 minutes, air cool to RT	225	2[illegible]	6	LH 950
			Hold at 950 F ± 10 F, 2 hours, plus 900 F ± 10 F, 3 hours, plus 850 F ± 10 F, 3 hours	250	23[illegible]	6	[illegible]
CH		Cold rolled 60% at mill		220	190	5	C
			Heat to 900 F ± 10 F, hold for [illegible], air cool to RT	265	260	2	CH 900

FIGURE 11. TREATMENT AND TYPICAL PROPERTIES OF 17-7 PH

The TH sequence of treatments was the first ever applied to 17-7 PH. This hardening sequence results in lower strength, but better ductility, than the other sequences. No subzero treatment is required.

The RH sequence of treatments develops the best strength obtainable in 17-7 PH by heat treatment alone. Somewhat less 17-7 PH is treated by the RH sequence than by the TH sequence.

The LH sequence of treatments is new. The mechanical properties developed are about the same as those resulting from the RH sequence of treatments. The lower conditioning temperature used in the LH sequence, however, reduces problems of scaling and warping. Despite this to recommend it, there is no evidence to indicate that the LH sequence is being used.

Multiple hardening is an option in either the RH or LH sequence. It adds about 20,000 to 25,000 psi to both the yield and the tensile strengths. A longer aging treatment is required.

If formability can be compromised, it is possible to get highest strength in material transformed by cold rolling 60 per cent at the mill (Condition C). As shown in Figure 11, aging is the only thermal treatment performed by the fabricator. Somewhat less 17-7 PH is sold in Condition C than in Condition A.

Condition TH 1050

As shown in Figure 11, 17-7 PH is treated to Condition TH 1050 by conditioning at 1400 F, transforming at 60 F, and aging at 1050 F. This is the sequence termed "double heat treatment". About 60 per cent of the 17-7 PH sold in Condition A is treated to obtain Condition TH 1050.

Conditioning. After fabrication, the TH hardening sequence begins with a conditioning treatment at 1400 F for 90 minutes. During this treatment chromium carbide particles precipitate at grain boundaries or in other regions of high energy, e.g., active slip planes. The precipitation, by reducing the effective carbon and chromium content of the austenite, triggers it for transformation on subsequent cooling. As shown in the following tabulation (Condition T), only 0.016 per cent carbon remains in solution after treatment at 1400 F.

17-7 PH	Carbon, per cent	
Condition	In Solution	In Precipitated Carbides
A	0.064	0.006
T	0.016	0.054
TH 1050	0.008	0.062
R-100	0.034	0.036
RH 950	0.026	0.044
L	0.015	0.055
LMH	0.014	0.056

Conditioning at 1400 F is designed to provide the best combination of strength and ductility in material subsequently transformed by cooling to 60 F and aged. Maximum strength, but poorer ductility, is obtained by conditioning at 1300 F. On the other hand, material that has been severely cold worked does not respond well to treatment at 1400 F. Severely cold-worked stock should be conditioned at 1550 F for 90 minutes. This treatment not only conditions the matrix, but also makes austenitic any portions that were transformed by working. 17-7 PH treated at 1550 F, however, must be cooled to 0 F to be martensitized.

Treatment at 1400 F for more than 90 minutes increases, somewhat, the yield strength of material in Condition TH 1050. Treatment for less than 90 minutes has the opposite effect.

Transforming. On cooling from the 1400 F conditioning treatment, martensite begins to form at about 200 F. The reaction continues as temperature is reduced; it is completed by cooling to 60 F and holding at that temperature for 30 minutes. It is important to continue the cooling to 60 F within 1 hour to assure complete transformation. Any delay in the cooling, failure to cool to 60 F, or holding at 60 F for less than 30 minutes, can result in incomplete transformation. This, in turn, reduces final strength.

Material severely cold worked and, therefore, conditioned at 1550 F transforms over a somewhat depressed temperature range. It is necessary to cool this material to 0 F to effect complete transformation.

17-7 PH conditioned at 1400 F, or 1550 F, and transformed by proper cooling is designated by Condition T. Some typical properties of 17-7 PH in Condition T are illustrated in Figure 11.

Aging. A substantial increase in strength and hardness is obtained by aging transformed material. This hardening is thought to be the result of the coherent precipitation of a second phase. Early evidence indicated that the precipitate was a compound of aluminum and nickel. More recent work, however, suggests that the precipitate is body-centered cubic in structure and ordered, with iron on one sublattice and chromium, nickel, and aluminum on the other. Some additional carbides also precipitate during aging.

Hardening during aging takes place over a wide range of temperatures. It can be discerned at 200 F, reaches a maximum at 950 F, and tapers off as 1400 F is approached. Although peak strength can be obtained by aging at 950 F, it is accompanied by minimum ductility. Aging at 1050 F, while it results in somewhat reduced strength, yields an improved combination of strength and ductility. Some typical properties of 17-7 PH in Condition TH 1050 are given in Figure 11 Others may be found in Appendix E-1.

At 1050 F, maximum strength is developed in the first few minutes of aging. Thereafter strength decreases gradually with time. The 90-minute aging time is specified because it results in good uniformity of properties and satisfactory bend ductility.

Variations in the aging treatment are the most convenient way for a fabricator to alter the final properties of 17-7 PH. It is not unusual for material to be treated to Condition TH 1075, or Condition TH 1100, when extra ductility is desired.

Dimensional Changes. During the transformation of austenite to martensi. 17-7 PH expands by 0.0043 to 0.0051 inch/inch. On subsequent aging at 1050 F precipitation and a slight reversion of martensite to austenite results in a contraction, usually 0.0004 to 0.0009 inch/inch. The net dimensional change seldom is less than 0.0037 inch/inch or more than 0.0047 inch/inch. These changes must be considered in the design of critical parts and assemblies

Condition RH 950

The RH hardening sequence is somewhat longer than the TH sequence in that it involves subzero cooling. After conditioning at 1750 F, 17-7 PH is transformed by subzero cooling. Final properties are obtained by aging. This sequence of treatments is diagramed in Figure 11. About 40 per cent of the 17-7 PH sold in Condition A is treated by the RH sequence.

Conditioning. If the RH sequence is to be used, 17-7 PH is conditioned at 1750 F. As shown in the tabulation on page 42 (Condition R-100), 0.034 per cent carbon remains in solution after conditioning; the balance precipitates in the form of chromium carbide particles. The effect of this treatment is to raise the M_s to about room temperature. Thus material conditioned at 1750 F remains austenitic on cooling to room temperature, but it can be transformed by cooling to -100 F.

Material triggered at 1750 F is designated Condition A-1750. Some typical properties of 17-7 PH in Condition A-1750 are illustrated in Figure 11.

Conditioning temperatures greater than 1750 F depress the martensite transformation range, and subsequent cooling to -100 F may not result in complete transformation. Conditioning temperatures less than 1750 F allow some martensite to form when the material is cooled to room temperature. Unless cooling to -100 F is started immediately, this martensite tends to stabilize the balance of the austenite against transformation on subsequent cooling.

Transforming. Material in Condition A-1750 is transformed by cooling it to -100 F and holding it at that temperature for 8 hours. Material having received this treatment is designated Condition R-100. Most of the transformation occurs during cooling to -100 F and during the first hour at this temperature. Significant additional transformation, however, may occur through the eighth hour.

Some typical properties of 17-7 PH in condition R-100 are illustrated in Figure 11. The strength of material in Condition R-100 is somewhat greater than that of material in Condition T. The strength differential is due to the slightly higher carbon content of the martensite in Condition R-100, 0.034 per cent versus 0.016 per cent.

<u>Aging</u>. The standard aging treatment for material in Condition R-100 is 950 F for 1 hour. This treatment greatly strengthens 17-7 PH; it results in Condition RH 950. Some typical properties of 17-7 PH in Condition RH 950 are shown in Figure 11; others are given in Appendix E-2.

Aging at temperatures considerably higher or lower than 950 F results in lower strength. Higher aging temperatures, however, are specified when higher ductility is desired. In recent practice much more 17-7 PH has been treated to Condition RH 1050 or Condition RH 1075 than to Condition RH 950. Although properties are not highly sensitive to time at 950 F, strength decreases significantly with increasing time at 1050 F.

A recently developed aging treatment, termed multiple hardening, results in improved strength. Material is aged at 950 F for 2 hours, cooled to 900 F and aged at that temperature for 3 hours, then cooled to 850 F and aged there for an additional 3 hours. This series of aging treatments results in Condition RMH. The cooling between the three stages of aging is not critical. Material in Condition RMH, as shown in Figure 11, is typically 20,000 to 25,000 psi stronger than material in Condition RH 950.

<u>Dimensional Changes</u>. During the transformation of austenite to martensite at -100 F, 17-7 PH expands by 0.0046 to 0.0052 inch/inch. During subsequent aging at 950 F it contracts by 0.00028 to 0.00036 inch/inch. Thus the net change in dimension is usually 0.0043 to 0.0049 inch/inch.

Most often the dimensional changes encountered during the hardening of 17-7 PH can be compensated for in the design of the forming dies. Small variations in the dimensional change, however, can result in serious misfits in very-close-tolerance parts and assemblies. If these are simple in shape, though, they may be held to close tolerances by cryoforming. The formed part is clamped in its die and the entire assembly is refrigerated at -100 F. The expansion that occurs during martensite formation increases flange width, but critical dimensions are maintained by the die. Stainless dies, backed by a rigid material, such as concrete, are used.

Another means of combatting nonuniform growth has been used from time to time. Only parts that can be stretch formed uniformly by 10 to 15 per cent are eligible. Material in Condition A-1750 is transformed almost completely during such a forming operation. Thus, stretch-formed parts need not be refrigerated, only aged. The expansion due to martensite formation is, of course, absorbed during forming.

<u>Condition LH 950</u>

The LH hardening sequence is new. It was developed for use where distortion and scaling during heat treatment must be minimized. The LH hardening sequence is diagramed in Figure 11. Some illustrative properties of 17-7 PH in Conditions LH 950 and LMH are given in this figure and in Appendix E-3. They are very similar to the properties of material in Condition RH 950.

The only difference in the LH and RH sequences is that LH calls for conditioning at 1180 F rather than at 1750 F as specified for the RH sequence. After treatment at

1180 F, 17-7 PH retains only 0.015 per cent carbon in solution. Thus, like material conditioned at 1400 F, it becomes martensitic on cooling to room temperature. The -100 F treatment is specified to assure complete transformation.

Because the LH hardening sequence is new, there is not yet any record of its being used. It does, however, offer the strength of RH material and a conditioning treatment less likely to cause warping and distortion.

Condition CH 900

In some applications, e.g., handsaws and valve diaphragms, high yield strength is required and formability is unimportant. For these applications 17-7 PH is purchased as cold rolled, Condition C. After any manufacturing operations the fabricator need only age the steel to obtain final high-strength properties. Somewhat less 17-7 PH is sold in Condition C than in Condition A. The CH sequence is diagramed in Figure 11.

Transforming. 17-7 PH destined for Condition CH 900 is transformed at the mill by cold rolling 60 per cent. Some illustrative properties of material in Condition C are given in Figure 11.

Aging. Material in Condition C is aged at 900 F for 1 hour to obtain Condition CH 900. Some illustrative properties of 17-7 PH in Condition CH 900 are shown in Figure 11; others may be found in Appendix E-4.

Fabrication

The fabricating characteristics of 17-7 PH are very similar to those of AISI 302. Some differences, however, must be kept in mind. 17-7 PH work hardens more rapidly than AISI 302. In addition, the formation of an adherent aluminum-containing scale during joining operations must be considered. Dimensional changes during heat treatment must be taken into account in the design of fabricating operations. Finally, 17-7 PH is a premium stainless steel that is sensitive to variations in handling; it deserves careful treatment.

Cutting. Operations such as blanking, punching, perforating, shearing, sawing, abrasive wheel cutting, and torch cutting are generally performed on 17-7 PH in Condition A. Procedures commonly used for AISI 302 also apply to 17-7 PH. But in laying out parts to be cut from material in Condition A, dimensional changes resulting from heat treatment should be anticipated.

Machining. 17-7 PH in Conditions A, A-1750, R-100, or T has somewhat better machinability than does AISI 302. Although the same machining speeds are used, 17-7 PH produces a chip that breaks up nicely. Material in Conditions TH 1050 and

RH 950 machines more slowly, but the same favorable chip characteristics are encountered. Just as in machining other stainless steels, it is important to use a feed heavy enough to get below the layer work hardened by the previous cut.

If material is machined in Condition A allowance must be made for the dimensional changes that occur during heat treating. In addition, the scale that forms during heat treatment will destroy the surface finish. If final machining is done on material in the transformed condition, however, the mild contraction that occurs on subsequent aging can often be tolerated or compensated for. The light tarnish does not destroy surface finish.

Forming. 17-7 PH in Condition A has forming characteristics similar to AISI 301. But, there are some differences. AISI 301 has an elongation in the order of 55 per cent; 17-7 PH in Condition A elongates only about 35 per cent. In addition, 17-7 PH expands during heat treatment subsequent to forming. For high dimensional accuracy it may be necessary to restrike parts in the transformed condition or to cryoform them.

Dimpling. 17-7 PH can be dimpled easily in Condition A. The dimensional change that occurs during subsequent treatment, however, makes for difficulty in aligning holes when hardened parts are joined. For this reason it may be necessary to dimple material in the transformed or fully hardened condition. This is difficult. A method based on high-frequency impact plus spinning, developed by Leinert Engineering, has been successful in dimpling fully hardened 17-7 PH in thicknesses from 0.020 inch to 0.120 inch.

Cleaning. Thorough cleaning of 17-7 PH prior to heat treatment facilitates scale removal. In addition, it is necessary to remove any lubricants or dirt that might contaminate the metal during a high-temperature treatment. Vapor degreasing will remove grease and drawing lubricants. Thereafter mechanical scrubbing with a mild abrasive cleaner will remove dirt and other insoluble materials. All traces of cleaners should then be removed by a thorough rinse with water. Finally, parts should be dried before annealing.

Annealing. 17-7 PH may be softened for further working by the solution heat treatment. This consists of a soak at 1950 F ± 25 F for 30 minutes per inch of thickness followed by a rapid cool at least to below 1000 F (cooling rate below 1000 F is not critical). For sheet thickness materials air cooling is sufficiently rapid.

Materials annealed in air develop a scale that can be easily removed later. Scale-free annealing is possible in a vacuum or in hydrogen, argon, or helium with a dew point below -65 F. Environments likely to cause nitriding, carburizing, or decarburizing should be avoided.

Descaling. The scale developed during heat treatment may be removed by a variety of methods. Wet grit blasting, however, is generally preferred to acid pickling. Material in Conditions A and CH 900 may be either blasted or pickled. The usual pickling treatment is immersion in a 10 per cent HNO_3-2 per cent HF aqueous solution on

at 110 to 140 F for a maximum of 3 minutes. Material in other conditions has been sensitized to rapid intergranular attack by the conditioning treatment and should be grit blasted rather than pickled.

Welding. 17-7 PH can be welded by many of the arc and resistance processes applicable to other stainless steels. No preheating, postannealing, or other complex procedures are required. The only major precaution that need be observed is to shield the weld area against loss of aluminum by oxidation.

Where high strength is not required, the weld metal may be a tough austenitic stainless steel, such as AISI 308. If high strength is desired 17-7 PH should be the filler metal and the entire structure should be rehardened starting with the solution heat treatment.

17-7 PH may be resistance welded in the hardened condition without subsequent rehardening.

Brazing. Furnace brazing is important largely in the construction of aircraft sandwich panels. Current practice is to use a sterling silver brazing alloy containing additions of indium, palladium, and lithium. This material has a flow temperature nearly corresponding to the conditioning temperature of the RH sequence. Assemblies are placed in a retort which is then purged, filled with an inert gas, and heated to the brazing temperature, about 1725 F.

Brazed panels cannot be cooled rapidly because they are large and in contact with tooling. If it is possible to cool them to 1000 F within 15 minutes, however, subsequent subzero cooling followed by aging at 1075 F results in yield strengths in the order of 180,000 psi.

PH 15-7 Mo

PH 15-7 Mo is a semiaustenitic precipitation-hardenable stainless steel developed, patented, and produced by the Armco Steel Corporation. It is also produced, under license, by Republic Steel Corporation. PH 15-7 Mo is a molybdenum-containing modification of 17-7 PH. It is largely a sheet and strip product, 17-4 PH or 17-7 PH are preferred for bar applications.

PH 15-7 Mo is somewhat stronger and somewhat more heat resistant than 17-7 PH, but more expensive.

PH 15-7 Mo bears the following AMS designations:

5520 A – Sheet, strip, and plate

5657 – Bars and forgings

Typical uses of PH 15-7 Mo follow those of 17-7 PH.

Composition

PH 15-7 Mo is a modification of 17-7 PH in which 2 per cent of the chromium is replaced with about 2.25 per cent molybdenum. Its composition is given below.

Element	Composition, per cent		
	Range	Nominal	Actual Example(a)
Carbon	0.09 max	0.07	0.070
Manganese	1.00 max	0.60	0.49
Phosphorus	0.04 max	--	0.016
Sulfur	0.04 max	--	0.017
Silicon	1.00 max	0.45	0.35
Chromium	14.00-16.00	15.00	15.32
Nickel	6.50-7.75	7.00	7.21
Molybdenum	2.00-3.00	2.25	2.26
Aluminum	0.75-1.50	1.20	1.18
Iron	Balance	Balance	Balance

(a) Heat No. 510 115.

Availability

PH 15-7 Mo is available in the same sizes and gages listed earlier in this report for 17-7 PH.

Treatment

With one exception, PH 15-7 Mo is treated exactly the same as 17-7 PH. In the LH hardening sequence, PH 15-7 Mo is conditioned at 1250 F; 17-7 PH is conditioned at 1180 F. Like 17-7 PH, the treatment of PH 15-7 Mo begins with a solution anneal at the mill. Thereafter it can be hardened by the TH, the RH, or the LH sequence. In addition, a small portion of PH 15-7 Mo is sold as transformed by cold rolling. The treatments applied to PH 15-7 Mo, together with some typical properties, are illustrated in Figure 12.

Condition TH 1050

PH 15-7 Mo can be treated to Condition TH 1050 by the same sequence of treatments used for 17-7 PH. The strength developed, however, is about the same as that of 17-7 PH in Condition RH 950. But, 17-7 PH is significantly cheaper than PH 15-7 Mo. Therefore when yield strengths on the order of 210,000 psi are desired, 17-7 PH in Condition RH 950 is specified much more often than is PH 15-7 Mo in Condition TH 1050. Very little of the PH 15-7 Mo sold is treated by the TH sequence.

Some typical properties of PH 15-7 Mo are given in Figure 12, and in Appendix F-1.

Condition RH 950

The great majority of PH 15-7 Mo is hardened by the RH sequence of treatments. This treatment, which is diagramed in Figure 12, is identical to that used for 17-7 PH. Although most properties have been measured on material aged at 950 F, today most material is aged at 1050 or 1075 F for greater toughness.

Conditioning. PH 15-7 Mo conditioned at 1750 F, as shown in the following tabulation, retains 0.033 per cent carbon in solution. The balance precipitates in the form of chromium carbides. On cooling to room temperature the austenitic structure of the matrix is retained.

PH 15-7 Mo Condition	Carbon, per cent: In Solution	Carbon, per cent: In Precipitated Carbides
A	0.064	0.002
T	0.013	0.053
TH 1050	0.002	0.064
R-100	0.033	0.033
RH 950	0.027	0.039
L	0.017	0.049

Treatment: Annealing	Treatment: Conditioning	Treatment: Transforming	Treatment: Aging	Typical Properties: Tensile Strength, 1000 psi	Typical Properties: Yield Strength, 1000 psi	Typical Properties: Elongation, per cent	Typical Properties: Designation
Mill annealed 1950 F ± 25 F				[illegible]	55	35	A
TH	Heat to 1400 F ± 25 F, hold for 90 minutes	Cool to 60 F +0/-10 F within 1 hour, hold for 30 minutes		145	40	[illegible]	T
			Heat to 1050 F ± 10 F, hold for 90 minutes, air cool to RT	[illegible]	200	7	TH 1050
RH	Heat to 1750 F ± 15 F, hold for 10 minutes, air cool to RT			150	55	[illegible]	A-1750
		Within 1 hour start cooling to -100 F ± 10 F, hold for 8 hours		180	125	7	R-100
			Heat to 950 F ± 10 F, hold for 60 minutes, air cool to RT	[illegible]	[illegible]	5	RH 950
			Hold at 950 F ± 10 F, 2 hours, plus 900 F ± 10 F, 2 hours, plus 850 F ± 10 F, 3 hours	[illegible]	[illegible]	5	[illegible]
LH	Heat to 1250 F ± 10 F, hold for 2 hours, air cool to RT	Cool to -100 F ± 10 F, hold for 8 hours					[illegible]
			Heat to 950 F ± 10 F, hold for 60 minutes, air cool to RT	[illegible]	[illegible]	5	LH 950
			Hold at 950 F ± 10 F, 2 hours plus 900 F ± 10 F, 2 hours plus 850 F ± 10 F, 3 hours	[illegible]	[illegible]	5	[illegible]
CH		Cold rolled 60% at mill		[illegible]	[illegible]	[illegible]	C
			Heat to 900 F ± 10 F, hold for 60 minutes, air cool to RT	[illegible]	[illegible]	[illegible]	CH 900

FIGURE 12. TREATMENT AND TYPICAL PROPERTIES OF PH 15-7 Mo

Transforming. PH 15-7 Mo conditioned at 1750 F is transformed by treatment at -100 F for 8 hours. For maximum strength the cooling to -100 F should begin within 1 hour of treatment at 1750 F. Conditioned austenite tends to become stabilized on holding at room temperature.

Aging. Transformed PH 15-7 Mo may be aged at 950 F, but more often it is aged at 1050 F or 1075 F. The higher aging temperatures result in somewhat lower strength, but in greater toughness.

Some typical properties of PH 15-7 Mo are shown in Figure 12; others may be found in Appendix F-2. Material in Condition RMH is about 20,000 psi stronger at room temperature than material in the RH 950 condition. Material in Condition RH 1050 is some 10,000 psi weaker than material in the RH 950 condition.

Dimensional Changes. During treatment from Condition A to Condition RH 950, PH 15-7 Mo undergoes a net expansion of about 0.0045 inch/inch.

Condition LH 950

There is no record that the LH sequence is being used to harden PH 15-7 Mo.

The LH hardening sequence, as shown in Figure 12, begins with a conditioning treatment at 1250 F. This is the lowest temperature at which carbides will precipitate in unstrained PH 15-7 Mo in a commercially feasible period. (In 17-7 PH this temperature is 70 F lower.) As shown in the tabulation on page 50, only 0.017 per cent carbon remains in solution after this treatment.

PH 15-7 Mo conditioned at 1250 F transforms on cooling to room temperature but complete transformation is assured by cooling to -100 F. Final strength is obtained by aging after the transformation.

The LH sequence of treatments offers the same mechanical properties as the RH sequence, but greater freedom from warping and scaling. Some illustrative properties of PH 15-7 Mo treated by the LH sequence are shown in Figure 12; others are given in Appendix F-3.

Condition CH 900

Very little PH 15-7 Mo is sold in the cold-rolled condition. The properties are about the same as those available in 17-7 PH and 17-7 PH is considerably cheaper. The only advantage offered by PH 15-7 Mo over 17-7 PH, both in Condition CH 900, is that PH 15-7 Mo will withstand somewhat higher temperatures than 17-7 PH.

Some illustrative properties of PH 15-7 Mo in Condition CH 900 are given in Figure 12; others may be found in Appendix F-4.

Fabrication

PH 15-7 Mo is fabricated in the same manner as 17-7 PH.

DCL:all

APPENDIX A-1

AM 350, DOUBLE AGED (DA)

APPENDIX A-1

AM 350, DOUBLE AGED (DA)

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation 2 Inches, per cent
-320	253	--	7.5
Room	174	144	14.0
400	163	123	8.5
500	164	122	9.5
600	166	126	11.5
700	172	118	10.0
800	166	112	10.5
900	144	98	12.0
1000	109	82	8.0

Compressive Properties

Temperature, F	0.20 Per Cent Offset Compressive Yield Strength, 1000 psi
Room	174.5
400	153.6
600	145.4
700	143.4
800	137.9

Elasticity Properties

Temperature, F	Modulus of Elasticity 1,000,000 psi
Room	30.3
400	28.2
500	27.8
600	24.7
700	24.6
800	24.2
900	24.1
1000	21.7

Stress-Rupture Properties

Temperature, F	Stress to Rupture, 1000 psi	
	100 Hours	1000 Hours
800	161	158
900	105	92
1000	58	50

Bearing Properties

E/D[a]	Direction	Ultimate Bearing Strength, 1000 psi	Bearing Yield Strength, 1000 psi
1.5	Longitudinal	275.0	212.7
	Transverse	277.1	212.5
2.0	Longitudinal	357.1	261.4
	Transverse	368.0	242.7

(a) $\frac{\text{Distance from edge of specimen to edge of hole}}{\text{Diameter of hole}}$

Corrosion Properties

Environment	Corrosion Rate, inches penetration per year
Boiling 65% nitric acid	0.065
Boiling citric acid	0.00062
Boiling glacial acetic acid	0.0004
Boiling 10% phosphoric acid	0.00010
10% oxalic acid at 200 F	0.02
1/2% sulfuric acid at 100 F	0.019

APPENDIX A-2

AM 350, SUBZERO COOLED AND TEMPERED (SCT)

APPENDIX A-2

AM 350, SUBZERO COOLED AND TEMPERED (SCT)

Physical Properties

Density	7.8 g/cm^3: 0.282 lb/in.^{3}

Electrical Resistivity, microhm-cm

At 80 F	78.80
134 F	80.62
199 F	82.63
370 F	88.37
461 F	91.24
541 F	94.11
729 F	99.85
835 F	102.73
981 F	107.51
1162 F	112.77
1349 F	115.17

Coefficient of Linear Thermal Expansion, 10^{-6}/F

At -58-68 F	5.9
-100-68 F	5.9
-148-68 F	5.9
-238-68 F	5.5
-320-68 F	5.0
68-212 F	6.3
68-572 F	6.8
68-752 F	7.0
68-932 F	7.2
68-1150 F	7.2
68-1350 F	6.7
68-1550 F	7.0
68-1700 F	7.5

Thermal Conductivity, Btu/(hr)(ft^2)(F/ft)	
At 100 F	8.50
200 F	8.87
300 F	9.36
400 F	9.81
500 F	10.30
600 F	10.80
700 F	11.30
800 F	11.70
900 F	12.20

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation 2 Inches, per cent
-320	287	--	7.5
Room	203	170	13.0
400	188	141	8.5
600	189	136	7.0
700	190	128	8.0
800	186	125	9.5
900	166	111	9.0
1000	106	85	16.0

Compressive Properties

Temperature, F	0.20 Per Cent Offset Compressive Yield Strength, 1000 psi
Room	166
400	158
600	154
700	142
800	140

Elasticity and Rigidity Properties

Temperature, F	Modulus of Elasticity, 1,000,000 psi	Modulus of Rigidity, 1,000,000 psi
Room	29.4	11.3
400	27.3	10.4
600	25.9	9.8
700	25.2	9.6
800	24.3	9.3

Stress-Rupture Properties

Temperature, F	Stress to Produce Rupture, 1000 psi		
	10 Hours	100 Hours	1000 Hours
800	188	186	183
900	140	118	95

Creep Properties

Temperature, F	Stress to Produce Creep Rate, 1000 psi	
	0.0001 Per Cent/Hour	0.00001 Per Cent/Hour
700	--	164
800	107	--

Fatigue Properties

Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Direction	Fatigue Strength at 10^7 Cycles, 1000 psi
187	154	Longitudinal	80
192	154	Transverse	82

Impact Properties

Temperature, F	Impact Strength (Charpy V-Notch), ft-lb
-320	4.3
-100	8.3
Room	14.1
212	24.5

Shear Properties

Temperature, F	Ultimate Shear Strength, 1000 psi	Shear-to-Tensile Ratio
70	137.7	0.66
	138.5	0.66
	141.4	0.68
400	123.6	0.62
	117.3	0.59
600	115.8	0.58
	117.5	0.59
800	123.8	0.65
	113.3	0.60
900	106.2	0.61
	107.1	0.61
1000	85.2	0.64
	91.1	0.69

Bearing Properties

Temperature, F	Bearing Yield Strength, 1000 psi	Ultimate Bearing Strength, 1000 psi	Bearing-to-Tensile Ratio	
			Yield	Ultimate
70	272.0	348.9	1.59	1.68
	309.4	441.4	1.78	2.11
	305.5	438.8	1.76	2.10
400	276.0	404.3	1.84	2.02
	278.1	396.8	1.85	1.98
600	266.8	386.5	1.89	1.93
	263.7	372.9	1.86	1.86
800	270.8	362.5	2.21	1.92
	267.7	356.9	2.18	1.89
900	267.7	345.2	2.24	1.98
	255.4	341.5	2.14	1.96
1000	205.2	295.4	2.08	2.23

Corrosion Properties

Environment	Corrosion Rate, inches per year
Boiling 65% nitric acid	0.014
Boiling citric acid	0.00003
Boiling glacial acetic acid	0.0004
Boiling 10% phosphoric acid	0.00010
10% oxalic acid at 200 F	0.02
1/2% sulfuric acid at 100 F	0.015

APPENDIX A-3

AM 350, COLD ROLLED AND TEMPERED (CRT)

APPENDIX A-3

AM 350, COLD ROLLED AND TEMPERED (CRT)

Tensile Properties

Cold Reduced, per cent	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches or 4 D
		Strip	
20	190	160	17
30	225	195	13
		Wire	
30	227	214	18
50	272	259	12
70	335	322	11

APPENDIX B-1

AM 355. DOUBLE AGED (DA)

APPENDIX B-1

AM 355, DOUBLE AGED (DA)

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
	Bar		
Room	187.8	152.9	16.5
300	173.9	137.9	13.0
600	174.5	130.3	9.0
700	172.9	118.6	11.0
800	166.8	117.2	11.0
900	151.7	105.3	12.0
1000	121.4	93.4	15.0
	Castings		
	175-191	135-150	10-16

Impact Properties

Temperature, F	Impact Strength (Charpy V-Notch), ft-lb
-90	4
0	7
18	9
150	17
300	24

Corrosion Properties

Environment	Corrosion Rate, inches per year
Boiling 65% nitric acid	0.04
Boiling citric acid	0.0004
Boiling glacial acetic acid	0.0007
Boiling 10% phosphoric acid	0.0137
10% oxalic acid at 200 F	0.04
1/2% sulfuric acid at 100 F	0.028

APPENDIX B-2

AM 355, SUBZERO COOLED AND TEMPERED (SCT)

APPENDIX B-2

AM 355. SUBZERO COOLED AND TEMPERED (SCT)

Physical Properties

Density: 7.81 g/cm^3; 0.282 lb/in.^{3}

Electrical Resistivity, microhm-cm

At 82 F	75.73
113 F	76.62
211 F	79.72
320 F	82.81
470 F	86.80
607 F	91.22
734 F	94.80
885 F	99.19
1052 F	103.61
1208 F	108.03
1394 F	109.80

Coefficient of Linear Thermal Expansion, 10^{-6}/F

At 68- 212 F	6.4
68- 572 F	6.8
68- 752 F	7.0
68- 932 F	7.2
68-1150 F	7.2
68-1350 F	6.5
68-1500 F	6.7
68-1700 F	7.1

Thermal Conductivity, Btu/(hr)(ft^2)(F/ft)

At 100 F	8.72
200 F	9.18
300 F	9.52
400 F	9.92
500 F	10.30
600 F	10.70
700 F	11.20
800 F	11.60
900 F	12.00

Magnetic Permeability

At 25 oersteds	45
50 oersteds	85
100 oersteds	74
200 oersteds	48
Maximum	86

Tensile Properties

Temperature, F	Tempering Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
		Bar		
Room	850	216	182	19.0
	1000	186	171	19.0
400	850	207	163	15.5
	1000	165	152	16.0
600	850	210	152	11.5
	1000	159	143	14.0
800	850	198	139	11.0
	1000	140	128	15.0
1000	850	144	97	16.0
	1000	115	96	19.0
		Sheet		
Room	850	222	185	15.0
400	850	202	149	8.5
600	850	204	143	8.5
700	850	197	135	10.0
800	850	190	124	10.0
1000	850	121	97	9.0

Tensile Properties (Continued)

Temperature, F	Tempering Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
	Castings			
Room	850	210-225	150-175	10-20
	1000	180	160	12
400	850	200	155	9
	1000	160	145	8
600	850	200	150	6
	1000	155	135	8
800	850	190	138	8
	1000	155	120	11
1000	850	125	100	12
	1000	115	100	18

Compressive Properties

Temperature, F	0.20 Per Cent Offset Compressive Yield Strength, 1000 psi
Room	215
400	180
600	174
700	165
800	160
1000	105

Elasticity Properties

Temperature, F	Modulus of Elasticity, 1,000,000 psi: Measured in Tension	Modulus of Elasticity, 1,000,000 psi: Measured in Compression	Modulus of Rigidity, 1,000,000 psi
Room	28.3	28.2	11.2
400	26.5	27.8	10.5
600	24.1	25.5	10.0
700	23.8	23.1	9.8
800	28.5	22.5	9.5
900	--	--	9.1
1000	19.7	20.9	--

Stress-Rupture Properties

Temperature, F	Tempering Temperature, F	Stress to Produce Rupture, 1000 psi: 10 Hours	100 Hours	1000 Hours
800	850	188	186	180
	1000	140	138	135
900	850	147	118	98
	1000	110	105	99
1000	850	87	70.5	57.5

Fatigue Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	Endurance Limit at 10×10^7 Cycles, 1000 psi
Room	214	107.5
800	214	55

Impact Properties

Temperature, F	Tempering Temperature, F	Impact Strength (Charpy V-Notch), ft-lb
-320	850	2.3
	1000	9.3
-100	850	9.3
	1000	24.3
10	850	14.5
	1000	37.7
70	850	17.1
	1000	45.5
212	850	38.5
	1000	50.1

Shear Properties

Temperature, F	Ultimate Shear Strength, 1000 psi	Shear-to-Tensile Ratio
Room	169.4	0.75
400	139.3	0.69
600	127.4	0.63
700	126.4	0.64
800	121.3	0.65
900	120.9	--
1000	96.5	0.80

Bearing Properties

Temperature, F	Ultimate Bearing Strength[a], 1000 psi	Bearing Yield Strength[a], 1000 psi
Room	415	305
400	384	290
600	378	282
800	362	268
900	333	240

(a) $\frac{\text{Distance from edge of specimen to edge of hole}}{\text{Diameter of hole}} = 2.$

Corrosion Properties

Environment	Corrosion Rate, inches per year
Boiling 65% nitric acid	0.03
Boiling citric acid	0.0001
Boiling glacial acetic acid	0.00007
Boiling 10% phosphoric acid	0.0032
10% oxalic acid at 200 F	0.04
1/2% sulfuric acid at 100 F	0.024

APPENDIX B-3

AM 355, COLD ROLLED AND TEMPERED (CRT)

APPENDIX B-3

AM 355, COLD ROLLED AND TEMPERED (CRT)

Physical Properties

Density 0.284 lb/in.^{3}

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
Room	233	215	20.5
400	209	186	6.0
600	202	171	7.0
800	186	149	8.0
900	174	144	6.0
1000	139	116	5.0

Compressive Properties

Temperature, F	0.20 Per Cent Offset Compressive Yield Strength, 1000 psi
Room	183
400	156
600	146
700	136
800	127
900	119
1000	112

Elasticity Properties

Temperature, F	Modulus of Elasticity, 1,000,000 psi	
	Measured in Tension	Measured in Compression
Room	29.0	28.7
400	25.9	26.8
600	24.6	25.5
700	--	24.8
800	24.1	23.9
900	23.7	21.6
1000	23.9	21.5

Stress-Rupture Properties

Temperature, F	Stress to Rupture, 1000 psi		
	10 Hours	100 Hours	1000 Hours
800	191	190	182
900	1[illegible]8	135	116
1000	110	85	65

APPENDIX B-3

AM 355, EXTRAHARD (XH)

APPENDIX B-4

AM 355, EXTRAHARD (XH)

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
Room	349	335	1.0
700	287	265	3.0
800	288	253	2.5
900	263	229	1.5
1000	181	155	4.5

Elasticity Properties

Temperature F	Modulus of Elasticity, 1,000,000 psi
Room	31.9
700	27.3
800	26.4
900	24.4
1000	22.6

APPENDIX B-5

AM 355. SUBZERO COOLED. COLD ROLLED. AND TEMPERED (SCCRT)

APPENDIX B-5

AM 355, SUBZERO COOLED, COLD ROLLED, AND TEMPERED (SCCRT)

Density 0.2805 lb/in.^{3}

Tensile Properties

Temperature, F	Direction of Test	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
Room	Longitudinal	288	287	1.0
	Transverse	293	280	2.5
200	Longitudinal	290	290	1.0
	Transverse	282.5	272	2.0
400	Longitudinal	282	274.5	1.0
	Transverse	281	258	1.5
600	Longitudinal	268.5	254.5	3.0
	Transverse	272.5	240	3.5
800	Longitudinal	249	236	2.5
	Transverse	255	224	4.0
900	Longitudinal	225	213	2.5
	Transverse	223.5	202	2.0
1000	Longitudinal	152.5	145.5	2.0
	Transverse	166.5	143.5	4.0

Compression Properties

Temperature, F	Direction	0.20 Per Cent Offset Compressive Yield Strength, 1000 psi
Room	Longitudinal	268
	Transverse	[illegible]
400	Longitudinal	263
	Transverse	283
600	Longitudinal	255
	Transverse	280
800	Longitudinal	230
	Transverse	270
900	Longitudinal	215
	Transverse	233
1000	Longitudinal	147
	Transverse	170

Elasticity Properties

Temperature, F	Modulus of Elasticity, 1,000,000 psi	
	Longitudinal	Transverse
Room	29.9	31.1
200	28.5	31.1
400	26.9	27.6
600	26.1	27.0
800	25.3	25.3
900	24.5	23.6
1000	20.3	23.6

Stress-Rupture Properties

Temperature, F	Stress to Produce Rupture, 1,000 psi		
	10 Hours	100 Hours	1000 Hours
800	250	244	225
900	185	127	86

APPENDIX C-1

AM 357, SUBZERO COOLED AND TEMPERED (SCT)

APPENDIX C-1

AM 357, SUBZERO COOLED AND TEMPERED (SCT)

Tensile Properties

Tempering Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
850	234	193	15
1000	183	169	16.5

APPENDIX C-2

AM 357, SHEAR FORMED

APPENDIX C-2

AM 357, SHEAR FORMED

Tensile Properties

Per Cent Shear Formed	Direction	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
24	Longitudinal	248	198	23.3
	Transverse	247	176	19.9
33	Longitudinal	269	252	14.5
	Transverse	279	225	14.5
65	Longitudinal	313	312	16.0
	Transverse	334	275	8.7
70	Longitudinal	311	304	15.0
	Transverse	329	270	8.0

APPENDIX C-3

AM 357, AUSFORMED

APPENDIX C-3

AM 357, AUSFORMED

Tensile Properties

Ausforming Temperature, F	Reduction, per cent	Direction	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
70	75	Longitudinal	340	338	12
70	75	Transverse	348	--	7
250	88	Longitudinal	348	316	20
250	88	Longitudinal	338	322	20
250	38	Transverse	388	--	6
400	75	Longitudinal	268	245	10
400	90	Longitudinal	32[illegible]	254	16
400	90	Longitudinal	335	267	16

APPENDIX C-4

AM 357, COLD ROLLED AND TEMPERED (CRT)

APPENDIX C-4

AM 357, COLD ROLLED AND TEMPERED (CRT)

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
Room	290.8	276.2	3.5
400	290.7	278.7	1.0
600	275.6	261.7	1.5
800	254.3	232.4	1.5
900	237.2	213.3	1.5
1000	155.4	136.4	4.0

Elasticity Properties

Temperature, F	Modulus of Elasticity, 1,000,000 psi
Room	25.9
400	26.6
600	24.6
800	23.1
900	21.5
1000	18.7

APPENDIX C-5

AM 357, EXTRAHARD (XH)

APPENDIX C-5

AM 357. EXTRAHARD (XH)

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.2 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
Room	333.0	320.8	2.5
400	327.8	319.9	1.5
600	326.7	302.6	1.0
800	295.9	278.2	1.5
900	251.8	235.7	2.0
1000	160.3	143.8	4.0

Elasticity Properties

Temperature, F	Modulus of Elasticity, 1,000,000 psi
Room	26.8
400	26.3
600	25.8
800	23.5
900	21.5
1000	18.3

APPENDIX C-6

AM-357, SUBZERO COOLED, COLD ROLLED, AND TEMPERED (SCCRT)

APPENDIX C-6

AM 357, SUBZERO COOLED, COLD ROLLED, AND TEMPERED (SCCRT)

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
Room	308.9	302.6	4.0
400	292.6	277.4	2.5
600	281.3	256.7	3.5
800	264.3	237.8	4.0
900	240.9	214.7	4.0
1000	157.6	[illegible]	5.5

Elasticity Properties

Temperature, F	Modulus of Elasticity, 1,000,000 psi
70	26.0
400	25.5
600	24.1
800	22.3
900	22.2
1000	18.6

APPENDIX D-1

AM 359, SUBZERO COOLED AND AGED (SCA)

APPENDIX D-1

AM 359, SUBZERO COOLED AND AGED (SCA)

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation in 2 Inches, per cent
		Sheet	
Room	225	224	6.5
		Bar	
Room	253	235	7.9
600	216	189	8.5
800	197	164	11.0
1000	136	112	18.0
1100	85.5	62	40.0

Elasticity Properties

Temperature, F	Modulus of Elasticity, 1,000,000 psi
Room	29.2
600	24.0
800	23.1
1000	19.2
1100	15.3

APPENDIX E-1

17-7 PH, CONDITION TH 1050

APPENDIX E-1

17-7 PH, CONDITION TH 1050

Physical Properties

Density	7.65 g/cm^3; 0.276 lb/in.^{3}
Electrical Resistivity, microhm-cm	82
Magnetic Permeability	
At 25 oersteds	132-194
50 oersteds	120-167
100 oersteds	60-99
200 oersteds	46-55
Maximum	134-208
Coefficient of Linear Thermal Expansion, 10^{-6}/F	
At 70-200 F	5.6
70-400 F	6.1
70-600 F	6.3
70-800 F	6.6
Thermal Conductivity, Btu/(hr)(ft^2)(F/ft)	
At 300 F	9.8
500 F	10.7
840 F	12.2
900 F	12.2

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.2 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches	Hardness, C Rockwell
-300	238	212	10.5	
-200	225	201	10.[illegible]	
-100	213	193	10.5	
Room	193	182	10	43
200	185	175	9	
400	174	165	7	
600	162	155	4	
700	155	145	5	
800	144	130	6	
900	124	9[illegible]	10	

Compressive Properties

Temperature, F	0.2 Per Cent Offset Yield Strength, 1000 psi
Room	195
400	174
600	161
800	128
900	100

Elasticity Properties

Temperature, F	Room-Temperature Modulus of Elasticity, 1,000,000 psi	Per Cent of Room-Temperature Modulus of Elasticity
Room	29.0	100
200		98
300		96
400		94.5
500		92.5
600		90.5
700		89.5
800		86.5
900		84
1000		80

Stress-Rupture Properties

Temperature, F	Stress to Rupture, 1000 psi		
	10 Hours	100 Hours	1000 Hours
600	--	170	158
700	154	130	122
800	128	110	90
900	98	78	52

Creep Properties

Temperature, F	Stress to Produce Creep Rate, 1000 psi	
	0.1 Per Cent in 1000 Hours	0.01 Per Cent in 1000 Hours
600	135	125
700	105	100
800	60	45
900	23	--

Fatigue Properties

Surface Condition	Ultimate Tensile Strength, 1000 psi	Endurance Limit at 15×10^6 Cycles, 1000 psi	Endurance Ratio
Not descaled	182.6	58	0.318
Pickled	175.3	55	0.313
Vapor blasted	182.6	75	0.411
Polished (120 grit)	182.1	80.5	0.442

Impact Properties

Temperature, F	Impact Strength (Charpy V-Notch), ft-lb
-300	2
-200	3
-100	4
Room	7
200	9
300	11
400	13
500	15
600	16
700	16
800	16
900	15
1000	13

Shear Properties

Temperature, F	Direction of Test	Ultimate Tensile Strength, 1000 psi	Shear Strength, 1000 psi	Shear-to-Tensile Ratio
Room	Longitudinal	194.5	136.5	0.702
	Transverse	194	136.4	0.703
200	Longitudinal	187	128.7	0.688
	Transverse	187	129.9	0.695
400	Longitudinal	175	122.5	0.700
	Transverse	176.5	119.3	0.676
600	Longitudinal	165.4	109.1	0.660
	Transverse	166.5	110.2	0.662
700	Longitudinal	155	102.8	0.663
	Transverse	155	103.7	0.669
800	Longitudinal	144	94.0	0.653
	Transverse	145	96.6	0.666
900	Longitudinal	120	84.3	0.702
	Transverse	121	85.6	0.707
1000	Longitudinal	89	68.4	0.769
	Transverse	90	69.9	0.777

Bearing Properties

E/D[a]	2 Per Cent Bearing Yield Strength, 1000 psi	Ultimate Bearing Strength, 1000 psi	Ultimate Tensile Strength, 1000 psi
1.5	270.4	354.6	184

(a) $\frac{\text{Distance from edge of specimen to edge of hole}}{\text{Diameter of hole}}$.

Stress-Corrosion Properties

Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches	Stress Level, 1000 psi	Days to Failure
190.6	178.8	9.0	89	No failures in 746 days
214.4	199.6	8.0	100.0	No failures in 746 days
190.6	178.8	9.0	133.6	No failures in 746 days
214.4	199.6	8.0	151.3	One specimen failed after 82 days, another after 118 days; three specimens did not fail in 746 days

Note: Specimens were exposed to marine atmospheres at Kure Beach (80-foot lot).

APPENDIX E-2

17-7 PH, CONDITION RH 950

APPENDIX E-2

17-7 PH, CONDITION RH 950

Physical Properties

Density	7.65 g/cm^3; 0.276 lb/in.^{3}	
Electrical Resistivity, microhm-cm	83	
Magnetic Permeability		
At 25 oersteds	82-88	
50 oersteds	113-130	
100 oersteds	75-87	
200 oersteds	44-53	
Maximum	119-135	
Coefficient of Linear Thermal Expansion, 10^{-6}/F		
At 0-70 F	5.7	
70-200 F	5.7	
70-400 F	6.6	
70-600 F	6.8	
70-800 F	6.9	
Thermal Conductivity, Btu/(hr)(ft^2)(F/ft)		
At 300 F	9.8	Estimated
500 F	10.7	Estimated
840 F	12.2	Estimated
900 F	12.2	Estimated
Normal Spectral Emissivity		
At 1500 F	0.361	
1600 F	0.342	
1800 F	0.325	
2000 F	0.309	
2200 F	0.292	

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches	Hardness, Rockwell C
	Condition RH 950			
Room	221	215	6	48
200	210	200	6	
400	196	179	5	
600	184	164	7	
700	175	154	9	
800	160	137	12	
900	133	113	16	
1000	93	76	26	
	Condition RMH			
	250	230	6	

Compressive Properties

Temperature, F	0.20 Per Cent Offset Yield Strength, 1000 psi
Room	227
400	202
600	193
800	171
900	154
1000	117

Elasticity Properties

Temperature, F	Room-Temperature Modulus of Elasticity, 1,000,000 psi	Per Cent of Room-Temperature Modulus of Elasticity
Room	29.0	100
200		98.5
300		[illegible]
400		95.5
500		93.5
600		91.5
700		89
800		86
900		82.5
1000		79

Stress-Rupture Properties

Temperature, F	Stress to Rupture, 1000 psi		
	10 Hours	100 Hours	1000 Hours
600	--	188	180
700	182	169	146
800	150	113	92
900	98	61	44

Creep Properties

Temperature, F	Stress to Produce Permanent Deformation, 1000 psi	
	0.1 Per Cent in 1000 Hours	0.2 Per Cent in 1000 Hours
600	105	126
700	60	87
800	31	36
900	12.5	14

Fatigue Properties

Surface Condition	Direction of Test	Ultimate Tensile Strength, 1000 psi	Endurance Limit at 5×10^6 Cycles, 1000 psi	Endurance Ratio
Not descaled	Transverse	228.1	82	0.36
Vapor blasted	Transverse	228.1	108	0.47
Vapor blasted	Transverse	238.8	114	0.48
Vapor blasted	Longitudinal	240.1	106	0.44

Impact Properties

Temperature, F	Impact Strength (Charpy V-Notch), ft-lb
-110	4.0
Room	4.0
100	5.7
200	7.2
300	11.2
400	12.0
500	12.7
600	12.5
700	11.5
800	12.3
900	11.0
1000	11.2

Shear Properties

Temperature, F	Direction of Test	Ultimate Tensile Strength, 1000 psi	Shear Strength, 1000 psi	Shear-to-Tensile Ratio
Room	Longitudinal	219.5	149.3	68.0
	Transverse	222.5	155.3	69.8
200	Longitudinal	209	122	58.4
	Transverse	214	147.7	69.0
400	Longitudinal	194	115.6	59.7
	Transverse	198	131.8	66.6
600	Longitudinal	183	113.7	62.1
	Transverse	185.5	121.2	65.3
700	Longitudinal	170	107.1	63.0
	Transverse	176	119.2	67.7
800	Longitudinal	158	99.3	62.8
	Transverse	161	112.3	69.8
900	Longitudinal	132	86.8	65.8
	Transverse	134	98.4	73.4
1000	Longitudinal	93	64.9	69.8
	Transverse	91.5	72.3	79.0

Bearing Properties.

E/D[a]	2 Per Cent Bearing Yield Strength, 1000 psi	Ultimate Bearing Strength, 1000 psi	Hardness, Rockwell C
2.0	379	463	47-48

(a) $\frac{\text{Distance from edge of specimen to edge of hole}}{\text{Diameter of hole}}$.

Stress-Corrosion Properties

Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches	Stress Level 1000 psi	Days to Failure
237.6	216.9	5.0	111.6	All five specimens failed in 16 to 49 days; average life was 30.2 days
230.2	217.5	5.0	110.2	One specimen failed after 116 days; 4 specimens did not fail in 746 days
237.6	216.9	5.0	167.5	All five specimens failed in 6 to 10 days; average life was 7.4 days
230.2	217.5	5.0	165.4	All five specimens failed in 26 to 71 days; average life was 51.6 days

Note: Specimens were exposed to marine atmospheres at Kure Beach (800-foot lot).

APPENDIX E-3

17-7 PH, CONDITION LH 950

APPENDIX E-3

17-7 PH. CONDITION LH 950

Tensile Properties

Condition	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
LH 950	225	209	6
LMH	250	230	6

APPENDIX E-4

17-7 PH, CONDITION CH 900

APPENDIX E-4

17-7 PH, CONDITION CH 900

Physical Properties

Density	7.67 g/cm^3; 0.277 lb/in.^{3}
Electrical Resistivity, microhm-cm	83.8
Magnetic Permeability	
At 100 oersteds	70
200 oersteds	43.5
Maximum	125
Coefficient of Linear Thermal Expansion, 10^{-6}/F	
At 70-200 F	6.1
70-400 F	6.2
70-600 F	6.4
70-800 F	6.6
Thermal Conductivity, Btu/(hr)(ft^2)(F/ft)	
At 300 F	9.5
500 F	10.6
840 F	12.5
900 F	12.5

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches	Hardness, Rockwell C
Room	262	247	5	49
200	253	238	4.5	
400	239	223	3.5	
600	224	204	3	
700	216	192	4	
800	205	176	5	
900	183	145	6	

Compressive Properties

Direction	0.20 Per Cent Offset Yield Strength, 1000 psi
Longitudinal	255
Transverse	300

Elasticity Properties

Direction	Tensile Modulus of Elasticity, 1,000,000 psi	Compressive Modulus of Elasticity, 1,000,000 psi
Longitudinal	29	31
Transverse	32	32.5

Stress-Rupture Properties

Temperature, F	Stress to Rupture, 1000 psi	
	100 Hours	1000 Hours
600	220	216
700	194	167
800	135	73
900	53	35

Fatigue Properties

Surface Condition	Direction of Test	Ultimate Tensile Strength, 1000 psi	Fatigue Strength, 1000 psi	
			10^7 Cycles	10^8 Cycles
Not descaled	Longitudinal	270	87	79.5
	Transverse	280	93	90.8
Pickled	Longitudinal	272	81.7	79
	Transverse	278	87.2	87.2
Polished (120 grit)	Longitudinal	259.4	84.5	80.6
	Transverse	276.6	97.5	91.0

Stress-Corrosion Properties

Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches	Stress Level, 1000 psi	Days to Failure
279.3	269.6	0.2	142.8	No failures in 746 days
279.3	269.6	0.2	214.2	No failures in 746 days

Note: Specimens were exposed to marine atmospheres at Kure Beach (200-foot lot).

APPENDIX F-1

PH 15-7 Mo, CONDITION TH 1050

APPENDIX F-1

PH 15-7 Mo, CONDITION TH 1050

Physical Properties

Density	7.685 g/cm^3; 0.277 lb/in.^{3}
Electrical Resistivity, microhm-cm	82
Magnetic Permeability	
At 25 oersteds	142
50 oersteds	147
100 oersteds	94
200 oersteds	55
Maximum	150
Coefficient of Linear Thermal Expansion, 10^{-6}/F	
At 70-200 F	6.1
70-400 F	6.1
70-600 F	6.1
70-800 F	6.3
70-900 F	6.5
70-1000 F	6.6
Thermal Conductivity, Btu/(hr)(ft^2)(F/ft)	
At 70 F	8.7
200 F	9.3
400 F	10.3
600 F	11.3
800 F	12.2
1000 F	13.2

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches	Hardness, Rockwell C
Room	211	204	6	44
200	205	200	5	
400	195	187	3	
600	182	171	4	
700	175	162	6	
800	165	150	9	
900	143	127	14	
1000	114	97	21	

Compressive Properties

Temperature, F	0.20 Per Cent Offset Yield Strength, 1000 psi
Room	217

Elasticity Properties

Temperature, F	Room-Temperature Modulus of Elasticity, 1,000,000 psi	Per Cent of Room Temperature Modulus of Elasticity
Room	29.0	100
200		98
300		96
400		94
500		92
600		89.5
700		87.5
800		84.5
900		81.5
1000		77.5

Stress-Rupture Properties

Temperature, F	Stress to Rupture, 1000 psi		
	10 Hours	100 Hours	1000 Hours
600	--	179	178
700	177	161	159
800	159	139	137
900	132	108	98

Impact Properties

Temperature, F	Impact Strength (Charpy V-Notch), ft-lb
Room	4
-40	3
-110	3
-320	3

Shear Properties

Temperature, F	Direction of Test	Ultimate Tensile Strength, 1000 psi	Shear Strength, 1000 psi	Shear-to-Tensile Ratio
Room	Longitudinal	211.5	143.8	0.680
	Transverse	217.5	142.3	0.654
200	Longitudinal	204	136.7	0.670
	Transverse	208	135.6	0.652
400	Longitudinal	194	125.7	0.648
	Transverse	--	124.6	--
600	Longitudinal	181.5	116.6	0.642
	Transverse	--	116.8	--
700	Longitudinal	173	107.6	0.622
	Transverse	176	110.5	0.628
800	Longitudinal	165	103.5	0.627
	Transverse	168	103.8	0.617
900	Longitudinal	143.5	94.3	0.657
	Transverse	--	95.5	--
1000	Longitudinal	[illegible]5.5	80.7	0.699
	Transverse	--	80.5	--

Bearing Properties

Sheet Thickness, inch	Direction	E/D[a]	2 Per Cent Bearing Yield Strength, 1000 psi	Ultimate Bearing Strength, 1000 psi
0.064	Longitudinal	1.5	339	402
		2.0	345	497
	Transverse	1.5	325	410
		2.0	378	463
0.050	Longitudinal	1.5	316	418
		2.0	342	501
	Transverse	1.5	343	427
		2.0	342	504

(a) $\frac{\text{Distance from edge of specimen to edge of hole}}{\text{Diameter of hole}}$

Stress-Corrosion Properties

Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches	Stress Level, 1000 psi	Days to Failure
213.8	204.6	5.5	197.4	No failures in 746 days
218.3	208.6	7.0	109.2	No failures in 746 days
213.8	204.6	5.5	161	One specimen failed after 75 days, another after 116 days, a third after 118 days; two specimens did not fail in 745 days
218.3	208.6	7.0	163.9	All five specimens failed in 20 to 70 days; average life was 37.8 days

Note: Specimens were exposed to marine atmosphere at Kure Beach (800-foot lot).

APPENDIX F-2

PH 15-7 Mo CONDITION RH 950

APPENDIX F-2

PH 15-7 Mo CONDITION RH 950

Physical Properties

Density	7.660 g/cm^3; 0.277 $lb/in.^3$
Electrical Resistivity, microhm-cm	83
Magnetic Permeability	
At 25 oersteds	65
50 oersteds	116
100 oersteds	87
200 oersteds	53
Maximum	119
Mean Coefficient of Thermal Expansion, 10^{-6}/F	
At 70-200 F	5.0
70-400 F	5.4
70-600 F	5.6
70-800 F	5.9
70-900 F	6.0
70-1000 F	6.1
Thermal Conductivity, Btu/(hr)(ft^2)(F/ft)	
At 70 F	8.7
200 F	9.3
400 F	10.2
600 F	11.1
800 F	12.0
900 F	12.5
Normal Spectral Emittance	
At 1500 F	0.395
1600 F	0.399
1800 F	0.3[illegible]
2000 F	0.370
2200 F	0.359

Tensile Properties

Temperature, F	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches	Hardness, Rockwell C
	Condition RH 950			
-100	251	235	7	48
Room	238	220	5	
200	227	208	5	
400	211	190	4	
600	203	170	5	
700	195	160	6	
800	182	149	9	
900	161	128	11	
1000	130	101	13	
	Condition RMH			
Room	257	235	[illegible]	52

Compressive Properties

Temperature, F	0.20 Per Cent Offset Yield Strength, 1600 psi
Room	243
400	211
600	204
800	194
1000	120

Elasticity Properties

Temperature, F	Room-Temperature Modulus of Elasticity, 1,000,000 psi	Per Cent of Room Temperature Modulus of Elasticity
Room	29.0	100
200		98
300		96
400		94
500		92
600		89.5
700		87
800		84.5
900		81.5
1000		77.5

Stress-Rupture Properties

Temperature, F	Stress to Rupture, 1000 psi		
	10 Hours	100 Hours	1000 Hours
600	--	202	200
700	200	193	191
800	190	174	171
900	168	125	108

Creep Properties

Temperature, F	Stress to Produce Permanent Deformation, 1000 psi	
	0.1% in 1000 Hours	0.2% in 1000 Hours
600	131.5	150
700	120.5	142
800	93	109
900	36	40.5

Fatigue Properties

Sheet Direction	(R = 0.6) Maximum Stress, 1000 psi	Cycles	Remarks
Longitudinal	190	39,000	Failed
	190	97,000	Failed
	180	43,000	Failed
	180	236,000	Failed
	170	90,000	Failed
	170	1,191,000	Failed
	160	10,478,000	Did not fail
	160	10,055,000	Did not fail
	150	10,092,000	Did not fail
	145	6,772,000	Failed
	145	10,141,000	Did not fail
	140	14,416,000	Did not fail
Transverse	180	46,000	Failed
	170	67,000	Failed
	170	131,000	Failed
	165	6,758,000	Failed
	160	6,351,000	Failed
	160	10,936,000	Did not fail
	150	10,071,000	Did not fail
	145	10,064,000	Did not fail
	145	10,154,000	Did not fail

Impact Properties

Temperature, F	Impact Strength (Charpy V-Notch), ft-lb
Room	4
-40	4
-110	3
-320	3

Shear Properties

Temperature, F	Direction of Test	Ultimate Tensile Strength, 1000 psi	Shear Strength, 1000 psi	Shear-to-Tensile Ratio
Room	Longitudinal	235.5	158.3	0.672
	Transverse	241.5	162.6	0.673
200	Longitudinal	227	151.7	0.668
	Transverse	231	155.8	0.674
400	Longitudinal	214.5	141.3	0.658
	Transverse	215	137.1	0.638
600	Longitudinal	204	130.4	0.639
	Transverse	205	129.1	0.630
700	Longitudinal	192	125.7	0.655
	Transverse	195	123.4	0.633
800	Longitudinal	181	118.7	0.655
	Transverse	184	115.7	0.629
900	Longitudinal	160	107.4	0.671
	Transverse	161	104.2	0.647
1000	Longitudinal	129.5	89	0.689
	Transverse	129	87.6	0.679

Bearing Properties

Sheet Thickness, inch	Direction	E/D[a]	2 Per Cent Bearing Yield Strength, 1000 psi	Ultimate Bearing Strength, 1000 psi
0.064	Longitudinal	1.5	350	455
		2.0	390	543
	Transverse	1.5	366	[illegible]
		2.0	372	507
0.050	Longitudinal	1.5	344	470
		2.0	[illegible]	564
	Transverse	1.5	345	476
		2.0	349	487

(a) $\frac{\text{Distance from edge of specimen to edge of hole}}{\text{Diameter of hole}}$

Stress-Corrosion Properties

Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches	Stress Level, 1000 psi	Days to Failure
244.6	219.8	4.2	115.8	All five specimens failed in 112 to 385 days; average life was 169.4 days
246.2	220.8	4.5	116.8	All five specimens failed in 10 to 116 days; average life was 95.8 days
244.6	219.8	4.2	173.7	All five specimens failed in 67 to 70 days; average life was 68.5 days
216.2	220.8	4.5	175.2	All five specimens failed in 7 to 24 days; average life was 14.2 days

Note: Specimens were exposed to marine atmospheres at Kure Beach (800-foot lot).

APPENDIX F-3

PH 15-7 Mo, CONDITION LH 950

APPENDIX F-3

PH 15-7 Mo, CONDITION LH 950

Tensile Properties

Condition	Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
LH 950	234	216	5
LMH	257	235	5

APPENDIX F-4

PH 15-7 Mo. CONDITION CH 900

APPENDIX F-4

PH 15-7 Mo, CONDITION CH 900

Tensile Properties

Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches
265	260	2

Stress-Corrosion Properties

Ultimate Tensile Strength, 1000 psi	0.20 Per Cent Offset Yield Strength, 1000 psi	Elongation, per cent in 2 inches	Stress Level, 1000 psi	Days to Failure
261.8	251.6	1.8	131.0	No failures in 746 days
261.8	251.6	1.8	196.6	No failures in 746 days

Note: Specimens were exposed to marine atmospheres at Kure Beach (800-foot lot).

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46D	Department of Defense Titanium Sheet-Rolling Program – Uniform Testing Procedure for Sheet Materials, September 12, 1958 (PB 121649 $1.25)
46E	Department of Defense Titanium Sheet-Rolling Program – Thermal Stability of the Titanium Sheet-Rolling-Program Alloys, November 25, 1958 (PB 151061 $1.25)
46F	Department of Defense Titanium Sheet-Rolling Program Status Report No. 4, March 20, 1959 (PB 151065 $2.25)
46G	Department of Defense Titanium Sheet-Rolling Program – Time-Temperature-Transformation Diagrams of the Titanium Sheet-Rolling Program Alloys, October 19, 1959 (PB 151075 $2.25)
46H	Department of Defense Titanium Sheet-Rolling Program, Status Report No. 5, June 1, 1960 (PB 151087 $2.00)
46I	Statistical Analysis of Tensile Properties of Heat-Treated Ti-4Al-3Mo-1V Sheet, September 16, 1960 (PB 151095 $1.25)
46J	Statistical Analysis of Tensile Properties of Heat-Treated Ti-4Al-3Mo-1V and Ti-2.5Al-16V Sheet, June 6, 1961 (AD 259284 $1.25)
106	Beryllium for Structural Applications, August 15, 1958 (PB 121648 $3.00)
107	Tensile Properties of Titanium Alloys at Low Temperature, January 15, 1959 (PB 151062 $1.25)
108	Welding and Brazing of Molybdenum, March 1, 1959 (PB 151063 $1.25)
109	Coatings for Protecting Molybdenum From Oxidation at Elevated Temperature, March 6, 1959 (PB 151064 $1.25)
110	The All-Beta Titanium Alloy (Ti-13V-11Cr-3Al), April 17, 1959 (PB 151066 $3.00)
111	The Physical Metallurgy of Precipitation-Hardenable Stainless Steels, April 20, 1959 (PB 151067 $2.00)
112	Physical and Mechanical Properties of Nine Commercial Precipitation-Hardenable Stainless Steels, May 1, 1959 (PB 151068 $3.25)
113	Properties of Certain Cold-Rolled Austenitic Stainless Sheet Steels, May 15, 1959 (PB 151069 $1.75)
114	Ductile-Brittle Transition in the Refractory Metals, June 25, 1959 (PB 151070 $2.00)
115	The Fabrication of Tungsten, August 14, 1959 (PB 151071 $1.75)
116R	Design Information on 5Cr-Mo-V Alloy Steels (H-11 and 5Cr-Mo-V Aircraft Steel) for Aircraft and Missiles (Revised), September 30, 1960 (PB 151072-R $1.50)
117	Titanium Alloys for High-Temperature Use Strengthened by Fibers or Dispersed Particles, August 31, 1959 (PB 151073 $2.00)
118	Welding of High-Strength Steels for Aircraft and Missile Applications, October 12, 1959 (PB 151074 $2.25)
119	Heat Treatment of High-Strength Steels for Aircraft Applications, November 27, 1959 (PB 151076 $2.50)
120	A Review of Certain Ferrous Castings Applications in Aircraft and Missiles, December 18, 1959 (PB 151077 $1.50)
121	Methods for Conducting Short-Time Tensile, Creep, and Creep-Rupture Tests Under Conditions of Rapid Heating, December 20, 1959 (PB 151078 $1.25)
122	The Welding of Titanium and Titanium Alloys, December 31, 1959 (PB 151079 $1.75)
123	Oxidation Behavior and Protective Coatings for Columbium and Columbium-Base Alloys, January 15, 1960 (PB 151080 $2.25)
124	Current Tests for Evaluating Fracture Toughness of Sheet Metals at High Strength Levels, January 28, 1960 (PB 151081 $2.00)
125	Physical and Mechanical Properties of Columbium and Columbium-Base Alloys, February 22, 1960 (PB 151082 $1.75)
126	Structural Damage in Thermally Cycled René 41 and Astroloy Sheet Materials, February 29, 1960 (PB 151083 $0.75)
127	Physical and Mechanical [illegible] of Tungsten and Tungsten-Base Alloys, March 15, 1960 (PB 151084 $1.75)
128	A Summary of Comparative [illegible] of Air-Melted and Vacuum-Melted Steels and Superalloys, March 28, 1960 (PB [illegible])
129	Physical Properties of Some Nickel-Base Alloys, May 20, 1960 (PB 151086 $2.75)
130	Selected Short-Time Tensile and Creep Data Obtained Under Conditions of Rapid Heating, June 17, 1960 (PB 151088 $2.25)
131	New Developments in the Welding of Metals, June 24, 1960 (PB 151089 $1.25)
132	Design Information on Nickel-Base Alloys for Aircraft and Missiles, July 20, 1960 (PB 151090 $3.00)
133	Tantalum and Tantalum Alloys, July 25, 1960 (PB 151091 $5.00)
134	Strain Aging of Refractory Metals, August 12, 1960 (PB 151092 $1.75)
135	Design Information on PH 15-7 Mo Stainless [illegible] for Aircraft and Missiles, August 22, 1960 (PB [illegible])

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136A	The Effects of Alloying Elements in Titanium. Volume A. Constitution. September 15, 1960 (PB 151094 $3.50)
136B	The Effects of Alloying Elements in Titanium. Volume B. Physical and Chemical Properties. Deformation and Transformation Characteristics. May 29, 1961 (AD 260226 $3.00)
137	Design Information on 17-7 PH Stainless Steels for Aircraft and Missiles. September 23, 1960 (PB 151096 $1.00)
138	Availability and Mechanical Properties of High-Strength Steel Extrusions. October 26, 1960 (PB 151097 $1.75)
139	Melting and Casting of the Refractory Metals Molybdenum, Columbium, Tantalum, and Tungsten. November 18, 1960 (PB 151098 $1.00)
140	Physical and Mechanical Properties of Commercial Molybdenum-Base Alloys. November 30, 1960 (PB 151099 $3.00)
141	Titanium-Alloy Forgings. December 19, 1960 (PB 151100 $2.25)
142	Environmental Factors Influencing Metals Applications in Space Vehicles. December 27, 1960 (PB 151101 $1.25)
143	High-Strength-Steel Forgings. January 5, 1961 (PB 151102 $1.75)
144	Stress-Corrosion Cracking - A Nontechnical Introduction to the Problem. January 6, 1961 (PB 151103 $0.75)
145	Design Information on Titanium Alloys for Aircraft and Missiles. January 10, 1961 (PB 151104 $2.25)
146	Manual for Beryllium Prospectors. January 18, 1961 (PB 151105 $1.00)
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150	A Review of Bending Methods for Stainless Steel Tubing. March 2, 1961 (PB 151109 $1.50)
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152	Binary and Ternary Phase Diagrams of Columbium, Molybdenum, Tantalum, and Tungsten. April 28, 1961 (AD 257739 $3.50)
153	Physical Metallurgy of Nickel-Base Superalloys. May 5, 1961 (AD 258041 $1.25)
154	Evaluation of Ultrahigh-Strength, Hardenable Steels for Solid-Propellant Rocket-Motor Cases. May 25, 1961 (AD 257976 $1.25)
155	Oxidation of Tungsten. July 17, 1961
156	Design Information on AM-350 Stainless Steel for Aircraft and Missiles. July 28, 1961 (AD 262497 $1.50)
157	A Summary of the Theory of Fracture in Metals. August 7, 1961
158	Stress-Corrosion Cracking of High-Strength Stainless Steels in Atmospheric Environments. September 15, 1961
159	Gas-Pressure Bonding. September 25, 1961
160	Introduction to Metals for Elevated-Temperature Use. October 27, 1961
161	Status Report No. 1 on Department of Defense Refractory Metals Sheet-Rolling Program. November 2, 1961
162	Coatings for the Protection of Refractory Metals From Oxidation. November 24, 1961
163	Control of Dimensions in High-Strength Heat-Treated Steel Parts. November 29, 1961

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1. Stainless steels - Heat treatment
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